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INSTITUTE FOR DEFENSE ANALYSES

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PREFACE

Beginning in April 2001, the Institute for Defense Analyses undertook a research effort aimed at discovering potential enhancements to the management of the Missile Defense Agency's long-term science and technology (S&T) program. The first phase of that effort produced a paper—*Science and Technology in Development Environments* (IDA Paper P-3764, May 2003)—that highlighted S&T management methods employed by successful public- and private-sector organizations. This paper follows up on that report by outlining how MDA could adapt and implement some of these management methods.

The authors wish to acknowledge the contributions of its distinguished senior advisory panel, all former directors of major S&T organizations: Peter Cannon (Rockwell Science Center), Arthur Chester (Hughes), and Lawrence Howell (General Motors). While their experiences shaped many of the findings and recommendations of this report, the final substantive and editorial judgments contained herein, as well as any factual errors or omissions, are the sole responsibility of the Institute for Defense Analyses.

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EXECUTIVE SUMMARY

Science and Technology in Development Environments,[*] the precursor of this Institute for Defense Analyses (IDA) study for the Missile Defense Agency (MDA), reviewed science and technology (S&T) management methods employed by successful public- and private-sector organizations. This report recommends an S&T management framework for MDA and describes in detail four areas that cover the range of earlier work deemed applicable to MDA's mission and structure:

- *Promoting Radical Innovation*—Fostering creative thinking, developing new missile defense concepts, and supporting emerging technologies.
- *Strategic Technology Steering and Execution*—Managing a portfolio of S&T projects in a limited number of technology areas critical to the long-term MDA mission.
- *Networking and Outreach*—Interacting with external communities to identify promising technologies, emerging threats, gaps in research, and partnering opportunities, as well as sustaining internal support for the MDA research program.
- *Analytical Techniques and Modeling and Simulation*—Supporting rigorous S&T planning and management within MDA using modern analytic techniques, tools and methods.

IDA also undertook a "pilot technology assessment" that experimented with some of these methods to identify specific candidate long-term S&T investments, looking out to the 2015–2020 time frame. IDA staff (and an independent, parallel effort at Sandia National Laboratories) developed innovative missile defense concepts and identified and assessed technologies that could enable them. Pilot project teams employed a systematic, top-down analysis process that proceeded from high-level missile defense challenges (boost-phase and terminal-phase missile defeat), to a functional description of novel operational concepts for addressing these challenges, to high-level systems descriptions that might realize the functions, to technical capabilities that could enable such systems

[*] R. Van Atta, R. Bovey, J. Harwood, W. Hong, A. Hull, B. Kindberg, and M. Lippitz, *Science and Technology in Development Environments*, IDA Paper P-3764 (Alexandria, Va.: Institute for Defense Analyses, May 2003).

to be built. A companion study describes the concepts developed and S&T investment candidates identified.†

OVERALL ORGANIZATION AND MANAGEMENT OF MDA STRATEGIC S&T

Figure ES-1 summarizes a proposed organizational framework for implementing the S&T management methods recommended in this report. MDA/AS refers to the Director for Advanced Systems within the current MDA organization. This individual would provide executive focus akin to the role often played by a Chief Technology Officer in a major corporation. Two new functions would be added to current MDA/AS responsibilities: strategic technology steering and innovation promotion activities under a Chief Innovation Executive. Each of these functions can be built gradually, beginning with a low level of staffing.

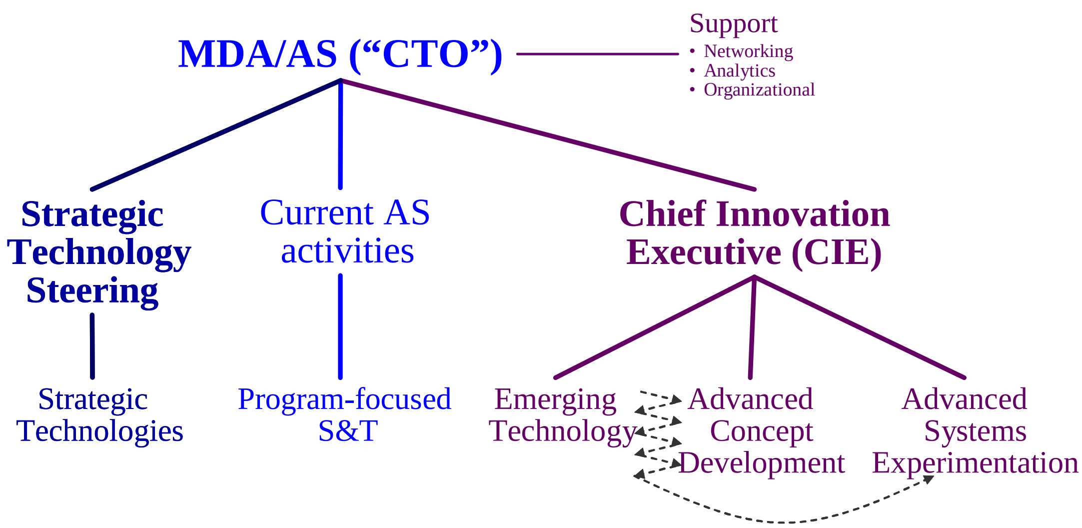

Figure ES-1. Recommended MDA/AS Long-Term S&T and Innovation Operation

The Chief Innovation Executive would lead efforts aimed at fostering technological and conceptual innovation to address broad missile defense challenges. An emerging technology group would scout, monitor, assess, and support immature technologies that, if successfully developed, could facilitate breakthrough improvements in ballistic missile defense systems, subsystems, and components. These groups would work closely and iteratively with advanced concept development teams to regularly propose, revise, and revisit concepts based on changing technologies and challenges. (The top-down concept development and technology identification effort explored in the

† Richard Van Atta et al., *Results of the Technology Assessment Pilot Project for the Missile Defense Agency* (Alexandria, Va.: Institute for Defense Analyses, forthcoming).

pilot technology assessment is one method that would be used.) The advanced systems experimentation group would undertake proof-of-concept projects for a small number of concepts matured through the interaction of emerging technology and advanced concept development efforts, with the goal of determining whether the integrated capabilities entailed should be considered as a candidate for development.

Strategic technology steering would be a management structure and set of activities for directing a portfolio of long-term S&T projects in specific technology areas deemed to be critical to the long-term success of the MDA mission. Support personnel could be brought on to assist the MDA/AS organization through networking, outreach, analysis, and organizational process management. Over time, MDA could consider forming high-level executive groups to help establish a long-range vision, balance the overall S&T program with respect to MDA strategic objectives, and overcome organizational barriers to the pursuit of new concepts.

PROMOTING RADICAL INNOVATION

MDA's mission objective raises complex capability challenges requiring significant innovation over the next few decades. Effectively encouraging radical innovation requires modification of traditional management processes and technology competencies. Innovation cannot be produced on command or on a fixed schedule, but well-designed processes can enable the right people to be vastly more effective and create a culture of innovation. Structured and informal interactions among people focused on technology and people focused on applications (both internal and external to the organization), along with linkages to overall organizational strategy, are critical factors that drive the evolution of an innovative organization. The following specific actions could be implemented over time:

- Appoint a Chief Innovation Executive to lead and support the overall effort.
- Recruit concept managers—These are individuals respected for their technical acumen who can bring together technologists, systems integrators, and operational experts from a variety of stakeholder organizations to identify and articulate the promise of a concept or technology, encourage its development, and garner top-level support.
- Form cross-functional innovation teams to systematically pursue mission needs discovery and definition, provide continuous technology monitoring and assessment, build and maintain a network of technical and application expertise relevant to MDA strategic challenges, perform regular outreach in

important technology communities, and provide professional support for project and process management.

- Support external S&T community engagement to remain cognizant of emerging technologies and foster new concepts.
- Develop management structures and internal capabilities, such as a customized "technology stage gate" process for screening and managing S&T candidate projects, independent experts groups, high-level review boards, and a knowledge base of past and present MDA S&T programs and innovation concepts.
- Form a separate Advanced Systems Experimentation Office focused on proof-of-concept experimentation and system-of-systems demonstration.

STRATEGIC TECHNOLOGY STEERING AND EXECUTION

Strategic technology steering comprises a management structure and set of activities useful for directing a portfolio of long-term S&T projects in a specific technology area determined to be critical to the long-term success of the MDA mission. An effective technology steering activity provides consistent long-term engagement and support for critical technology needs to maximize S&T productivity, effectiveness, and timeliness. Mechanisms can include identification of S&T gaps and opportunities and subsequent resource allocation, facilitation of internal and external technical communications and collaborations, formal technology management processes, and development of technical personnel. Technology steering should be sufficiently flexible to weather organizational restructurings and changing management personalities, organizational priorities, and mission needs. Specific steps over time could include the following:

- Establishing a strategic technology steering group focused on a selected technology, with a respected leader and—critically—direct reporting to supportive, committed top management.
- Supporting the strategic technology steering group with networking of related technology communities, potentially including creation of industry panels to allow contractor participation.
- Implementing a technology stage-gate process customized to address MDA's mission, planning horizon, and contract environment.
- Developing virtual laboratories: a highly collaborative form of S&T outsourcing employing formal, precompetitive coalition contracting structures to permit interaction of companies on S&T while protecting intellectual property rights.

NETWORKING AND OUTREACH

"Networking" refers to the processes used to interact with science and engineering communities inside and outside MDA to identify promising technologies, potential emerging threats, gaps in current research, and partnering opportunities. Outreach, typically directed toward MDA executive and program leaders, aims to gain support for a healthy long-term research program by demonstrating the need for it and documenting how it is supporting the MDA mission.

ANALYTICAL TECHNIQUES AND MODELING & SIMULATION

The planning and management of MDA's S&T program involves a wide range of functions, among them environmental scanning, development of research strategies to guide program planners and managers, determination of S&T focus areas, identification and development of project concepts, selection of research projects, management of ongoing projects, transition of research results, and infrastructure capabilities to support the research program. A large number of tools are available to support these S&T planning and management functions. Two examples of techniques MDA/AS should consider for near-term implementation are early stage-gate processes and scoring models for project evaluation and selection.

NEXT STEPS

The S&T management structures outlined here are general functions that have taken into account the general MDA mission and working environment but have not been specifically defined. To translate these ideas into formal processes for seeking, identifying, maturing, and eventually deciding upon options, MDA personnel will need to be directly involved in implementation, with MDA/AS actively engaged and overseeing the process. As next steps in MDA implementation, IDA proposes the following:

- Prepare an MDA/AS Strategic S&T Implementation Plan, including delineating the interrelationships among the proposed MDA(AS) S&T activities and other aspects of MDA S&T management, such as systems engineering, mission analysis, and systems architecture planning.
- Conduct workshops for MDA leadership and key participants to foster a uniform understanding of the S&T strategic concept and to develop the needed customized processes and tools.
- Complete current technology assessment studies and add new ones (e.g., midcourse defeat or close-in missiles). This should include doing the following:

- Undertaking detailed engineering assessments for selected concepts, leading to identification of specific technology gaps.
  - Making risk/cost assessment of identified technologies and consolidating these analyses into composite "grand challenges" across mission areas as well as candidate strategic technologies.
  - Performing validation experiments on promising concepts (e.g., explosively formed projectiles).
- Appoint/designate a Chief Innovation Executive and start building an innovation promotion organization to pursue identified key technology challenges, better define and document mission needs, systematically search for emerging technologies, and develop additional new concepts.
- Undertake formal networking activities to establish linkages with other government programs and to identify potential partners for future strategic technologies.
- Begin building an S&T candidate projects database to serve as an "organizational memory," enabling periodic revisiting of concepts and tracking of emerging technologies.
- Establish a traceable, quantitative scoring system, to permit concepts and technologies to be consistently ranked across concepts and over time.
- Assess options for virtual laboratories for ongoing long-term S&T execution.
- Determine the appropriate amount and type of modeling and simulation to support MDA S&T planning.

I. OVERALL ORGANIZATION AND MANAGEMENT OF MDA STRATEGIC S&T

Richard Van Atta, Michael Lippitz, and Robert Bovey

The precursor of this Institute for Defense Analyses (IDA) study for the Missile Defense Agency (MDA)[1] examined the science and technology (S&T) management methods of public- and private-sector organizations that had proved successful over time in building and maintaining dominant capabilities. The chapters that follow suggest how to begin implementing within MDA some of the most important categories of these methods: promoting radical innovation (Chapter II); strategic technology steering and execution (Chapter III); networking and outreach (Chapter IV); analytical techniques (Chapter V); and modeling and simulation (Chapter VI). This introductory chapter discusses the underlying ideas and context of these S&T management methods and outlines how they might be divided functionally within the MDA Advanced Systems and merged with existing MDA management processes.

UNDERLYING IDEAS AND CONTEXT

MDA was formed in January 2002 to consolidate Department of Defense (DoD) ballistic missile defense system (BMDS) programs. Service Operational Requirements Documents, which strictly defined desired system specifications for programs brought into MDA, were cancelled. Instead, an evolutionary, capability-based development approach was adopted. Under this approach, the overall BMDS was to evolve toward its ultimate objective—an integrated BMDS capable of providing a layered defense for the homeland, deployed forces, friends, and allies against ballistic missiles of all ranges in all phases of flight[2]—by deploying an initial system based on existing technologies, followed by a series of follow-on "blocks" incorporating improved technologies as they become available. This approach, known as "spiral development," stands in contrast to the traditional requirements-based development method (represented in the previous

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1 R. Van Atta, R. Bovey, J. Harwood, W. Hong, A. Hull, B. Kindberg, and M. Lippitz, *Science and Technology in Development Environments*, IDA Paper P-3764 (Alexandria, Va.: Institute for Defense Analyses, May 2003).

2 MDA mission statement, http://www.acq.osd.mil/bmdo/bmdolink/html/mission.html, 1 March 2004.

Operational Requirements Documents), in which the ultimate capability and technical approach were defined in advance, based on a well-specified threat.

In a capabilities-based, spiral-development approach, S&T research aims to identify and assess any technology advances that can meaningfully increase capabilities beyond what can be achieved currently. Internal guidance documents call for MDA to "examine the widest possible range of options to increase system capabilities… include(ing) assessing innovative approaches and new technology concept employment for land, air, sea and space-based application, potentially inserting enhancements at all levels of the BMDS: component, element, and system."[3] In the course of our research, we identified several ways to develop candidates for research work;

- Top-down mission analysis (such as the pilot technology assessment).
- Project reviews that identify shared problems or solutions.
- External and internal solicitations for new ideas, supported with appropriate funding.
- Technology scouting and assessment for applicability to the mission.
- Creative idea generation methods (such as providing staff with seed money to conceive and articulate novel ideas).

Several different types of research can emerge from these types of processes:

- *Strategic technologies*—technologies recognized as having long-term potential impact across several potential BMDS components.
- *Grand challenges*—critical general needs, without reference to particular technological means.
- *Solution paths*—specific approaches to solving a defined BMDS problem.

To develop significant new capabilities for future blocks, MDA will need to combine various research approaches into a robust, systematic, and *strategically focused* S&T effort. Because needed capabilities will not depend on a particular technical approach (which might be infeasible) or a particular definition of the threat (which might change), the overall effort should blend top-down, leadership-driven efforts with bottom-up, opportunity-driven, entrepreneurial processes. It should blend the following:

- Long-term focus on strategic technologies in well-defined domains with quick-turn exploration of crosscutting new concepts.

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3 BMDS Capability Enhancement Process, Version 5.0, 5 February 2003, Section 1.2, p. 5.

- Open-ended scientific experimentation to characterize unknown phenomenology with focused systems engineering to prove out integrated capabilities.
- Reliance on internal scientific and application expertise with leveraging of external sources of innovation. Where appropriate, it should apply rigorous systems analysis and metrics, but leaving room for open-ended (but not indefinite) exploration in other areas.

An example of this type of strategically focused S&T management occurred in the 1970s, when U.S. and North Atlantic Treaty Organization (NATO) planners and policy makers supported sustained concept development efforts to better define the Soviet military challenge and develop alternative responses to nuclear war. Panels, boards, and conferences, attended by both government personnel and independent experts, played an important role in the development, communication, review, and refinement of concepts. Although these gatherings were sponsored by government organizations, organizational agendas and detailed mission requirements did not constrain consideration of controversial ideas, and intermediate government organizations were often bypassed. Over time, these deliberations converged on defense concepts that emphasized standoff precision strike. The challenge of standoff precision strike was defined in detail, recognizing the need for

> integration of a wide range of technologies: target detection, recognition and location; delivery vehicles and munitions; and weapon navigation and guidance. This dictate(d) a unified approach to development in these areas and the establishment of operational procedures for effective integration and employment of both targeting and weapons systems.[4]

Respected defense analysts (involved in the deliberations) promoted standoff precision-strike concepts throughout the defense community and to top Office of the Secretary of Defense (OSD) and Service leadership. With the eventual imprimatur of top DoD leadership, resources increasingly focused on supporting strategic technologies and systems demonstrations associated with various precision-strike capabilities. These efforts are credited with fostering the conventional military superiority that the United States enjoys today.[5]

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4 "Final Report of the Advanced Technology Panel," *ARPA/DNA Long Range R&D Planning*, April 30, 1975, p. 6.

5 Van Atta et al. *Science and Technology,* pp. 10-11.

To test out the promise of such approaches in the current MDA context, IDA undertook a pilot project aimed at developing novel missile defense concepts and identifying needed technologies. Small groups of technical and applications experts focused on a few particular BMDS challenges. Through brainstorming, they identified a number of operational concepts that could potentially meet the challenges. A few of the more promising operational concepts were selected for more detailed examination, leading to high-level description of hypothetical systems that could carry out the operational concept. These systems concepts were reviewed to identify technology capabilities that might enable them. These technologies were assessed, and in some cases relatively broad areas of S&T in which research might well produce the knowledge needed to enable one or more of these technical capabilities were identified. Finally, the group proposed possible components of a specific, defined S&T program. Throughout the process, the group assessed and set priorities among concepts, systems, technology capabilities and S&T areas. (The detailed findings and conclusions of these efforts are described in Volume 2.)

The Buried Autonomous Anti-Missile System (BAAM) is one concept that illustrates how supporting synthetic thinking and systematic analyses can generate new solutions to important BMDS problems. BAAM contemplates deployment of small interceptor systems near enemy missile launch sites. These interceptor systems would detect local launches and attack the enemy missiles during their boost phase. If successfully developed, such systems could offer policy-makers important new options in addressing ballistic missile threats. Whereas most existing BMDS concepts contemplate a large-scale, integrated capability in which individual pieces are only effective in the context of a complex, layered system of systems, BAAM could permit numerous small, independent systems to be deployed. It would provide policy-makers with important new political and military options, transforming an important component of the ballistic missile defense problem. Many questions—technical, political, practical—need to be answered before pursuing such a system.

AN ORGANIZATIONAL REALIZATION

The top-down concept development and technology assessment effort, undertaken as a pilot project, is just one example of the type of productive interaction that can be fostered between applications-oriented and technology-oriented people. Figure I-1 summarizes how various scientific, engineering, and management elements of a long-term MDA S&T program could be realized organizationally, by balancing and channeling

top-down and bottom-up forces. MDA/AS refers to the Director for Advanced Systems within the current MDA organization. MDA/AS would provide executive focus for the overall MDA S&T effort, akin to the role often played by a Chief Technology Officer in a major corporation. "Current AS Activities," covers the current functions of the MDA/AS office, which were not investigated as part of the IDA project. The other elements in the figure do not currently exist in any structured, authoritative way within the MDA/AS office, and would have to be added. The new functions proposed here cover the missing S&T areas needed to support MDA: Innovation, the systematic exploration of new concepts and technology applications, and strategic technology, the systematic advance of technologies known to be critical to MDA's mission, regardless of specific system implementation.

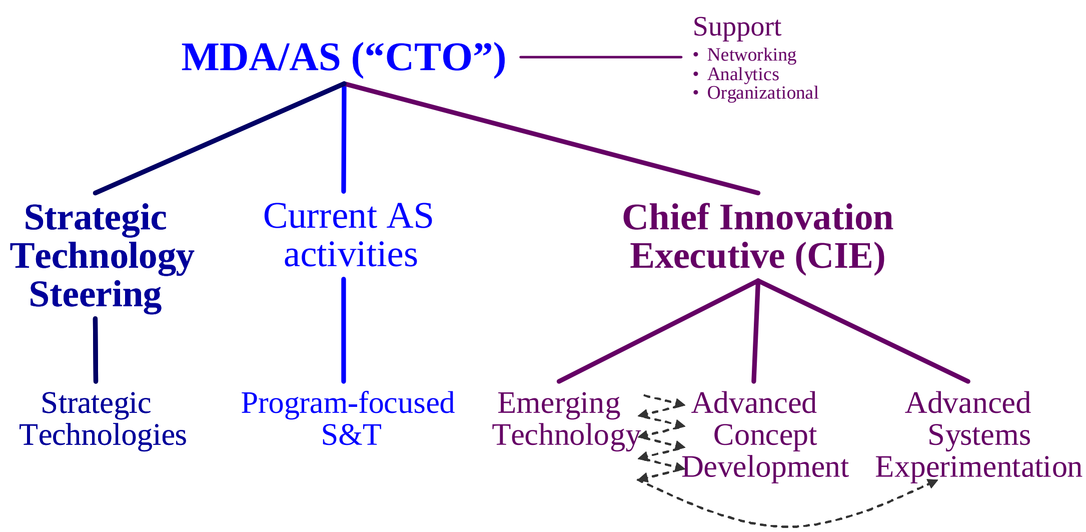

Figure I-1. Recommended MDA (AS) Long-Term S&T and Innovation Operation

The Chief Innovation Executive would lead a function that would foster and seek to build upon technological and conceptual innovation in meeting missile defense mission challenges. This position, which reports directly to the director of MDA/AS, would be designed to provide management stability through changes in MDA leadership. Long-term stability is needed because some of the projects and processes here may need continuity and consistent direction for a number of years to reach fruition. The Chief Innovation Executive would be primarily responsible for overseeing the development of the research agenda; providing the justification needed to support that agenda; overseeing the execution of the program: and recommending increases, reductions, or elimination of funding for individual research projects.

Reporting to the Chief Innovation Executive would be groups focused on emerging technology, advanced concepts development, and advanced systems experimentation. Emerging technology and advanced concept development form the core of the innovation operation. Emerging technologies responsibility would encompass scouting, monitoring, assessing, and supporting emerging technologies that could facilitate breakthrough improvements in BMDS, subsystems, and components. The top-down concept-development and technology-identification effort explored in the pilot tech assessment—moving explicitly from challenges to concepts to systems to technologies to S&T candidates—is one method that would be used as part of an ongoing advanced concept development effort that would regularly propose, revise, and revisit concepts based on changing technologies and challenges. Advanced systems experimentation would undertake proof-of-concept projects for those concepts that have matured sufficiently through the interaction of emerging technology and advanced concept development efforts and that are deemed to have the greatest promise for addressing BMDS challenges. The goal of advanced systems experimentation would be to determine whether the integrated capabilities entailed should be considered as candidates for formal development. As discussed in Chapter II, these groups could start with only a few people and evolve gradually.

Strategic technology steering would be another branch of the proposed new MDA/AS innovation organization. This organization would oversee a variety of activities for overseeing and directing a portfolio of long-term S&T projects in a small number of technology areas deemed to be critical to the long-term success of the MDA mission. Over time, MDA could consider forming high-level executive groups to support MDA/AS and the Chief Innovation Executive in establishing a long-range vision and support for long-term research, focusing and balancing the overall S&T program with respect to MDA strategic objectives, and to assist in overcoming organizational barriers to the pursuit of new concepts. Also over time, support personnel could be brought on to assist all of these MDA/AS efforts in networking, outreach, analysis, and organizational process management.

INTEGRATION WITH TOP-LEVEL MANAGEMENT SYSTEMS

"Innovative and scientific excellence are not sufficient—an organization must have mechanisms to link innovation to the businesses and customers, as well as to transition new developments from R&D to operations and the marketplace."[6]

MDA's central research program will require focus and management expertise to produce results. As a practical matter, it will be executed primarily by government contractors, but it must be managed with sufficient independence and crosscutting expertise to facilitate innovative approaches.[7] MDA's program elements are similar to many industry organizations in which semi-autonomous business units develop distinct systems. In such settings, central research in MDA needs to provide support that includes the following:

- Seeking and helping solve critical problems for program elements, in an internal consulting role (hence building organizational support for central research).
- Identifying new technologies that can either be integrated into existing systems or spawn new systems.
- Covering the technical gaps between program elements.
- Identifying common problems and solutions across program elements.
- Supporting technologies that span more than one program element, especially potential strategic technologies.[8]
- Seeking revolutionary new approaches to BMDS.
- Acting as networking center to bring ideas into MDA and to circulate ideas across MDA program elements.

To strengthen long-term research and innovation programs at MDA in this way, a concerted effort by the leadership of MDA over an extended period will be required. This effort will include the following:

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6 Van Atta, et al., *Science and Technology*.

7 Chapter III describes a variety of outsourcing structures that can create a robust research organization across technology areas beyond the scope of a single organization. Other options available for MDA include increases in the MDA/AS workforce or support contracting, support from a FFRDC, and outsourcing a defined scope of work to a single S&T organization such as the Naval Research Laboratory or the Army Research Laboratory.

8 The MDA Enhancement Plan is a vehicle for coordinating technology needs, development plans, costs, and schedules across MDA. It (1) provides the mix of concepts and technologies available to augment expected Block capabilities; (2) maps these concepts and technologies into augmentation roles; and (3) details processes for maturing, assessing, and infusing concepts and technology.

- Increasing and stabilizing funding for long-term research and fostering innovation.
- Making the organizational changes needed to establish and maintain the relevance of long-term research.
- Visibly promoting the need, both within and outside MDA, for focused long-term research, to support an effective S&T program in an organization that is currently focused on implementation.
- Supporting MDA/AS in implementing the long-term research program and in proving innovative missile defense concepts.

The S&T management structure established in MDA must maintain a balance between necessary program reviews from upper management and freedom to explore innovative technologies and solution paths that tend to move forward in fits and starts, with many dead ends along the way. There must also be a balance struck between the need to provide funding for a long-term research agenda and the need to support the immediate research challenges of current programs. The percentages devoted to each type of research will change over time, depending on immediate needs and the strategic direction of the organization. However, if top management fails to protect some percentage of the central research budget for long-term research and radical innovation, those funds will tend to be consumed by immediate needs. The need for patience and a long-term vision from top management was one of the most consistent themes in the precursor IDA report on S&T Management.

Over time, MDA could consider forming executive boards to support MDA/AS and the Chief Innovation Executive in establishing a long-range vision and support for long-term research, focusing and balancing the overall S&T program, and overcoming organizational barriers to the pursuit of new concepts. Such boards could provide stability through changes in leadership. Actual membership, charter, and operating procedures will have to be developed with MDA but initial thoughts are provided below:

- *Corporate S&T Oversight Board*—Members would include MDA's Deputy Director, Technical Director, and Technical Advisor. The Board would meet approximately twice a year: once as part of the budget process and a second time for a program review. Its primary functions should be to evaluate the long-term research program with respect to MDA's strategic objectives, provide final approval of the research agenda, and defend that agenda throughout MDA.
- *S&T Management Board*—This board would be chaired by the director MDA/AS and contain senior members from each of the individual MDA

system development programs. The primary functions of the board would be (1) to serve as a forum for the system development programs to recognize common long-term S&T issues, which might then be funded by MDA/AS, and (2) to offer perspectives on new concepts being pursued by MDA/AS and how the underlying capabilities might transition into future missile defense systems. The result of these deliberations would be a portfolio approach to the MDA S&T research agenda that supports the strategic objectives of MDA (beyond just the incremental needs of current systems programs), consistent with the funding goals and the direction provided by the Corporate S&T Oversight Board.

In addition to top-level management boards, the new concepts outlined in this report will need to be integrated with S&T management systems that MDA is in the process of establishing, as described in the "BMDS Integrated Program Plan." Figure 1-2 summarizes this management system. Many of the ideas described in the following chapters can be fit to this structure. For example, the AS database could serve as the "organizational memory" called for in Chapters II and III. Networking functions described in Chapter IV are consistent with the BMDS Enhancement Plan, which "will capture necessary information on external technology programs relevant to MDA (e.g., DARPA [Defense Advanced Research Projects Agency] projects, commercial technologies)." The "BMDS Utility Analysis" could be implemented as a Technology Value Model, one of the analytic efforts described in Chapter VI aimed at fostering consistently applied, quantitative judgment year after year so that comparisons can be made between judgments made in different years and mission sub-areas. Beyond the items in Figure I-2, strategic challenges would be informed by the MDA Technical Objectives and Goals documents, a view of threat in the Adversary Capability Document, and experiments run using the Adversary Vignettes Database. The options presented to the Director MDA for decision will be worked out between MDA/AS, the MDA Operational Concept Team, the Joint National Integration Center, and others. Annexes to the management documents above may be required to guide teams working to build a strategically focused S&T program.

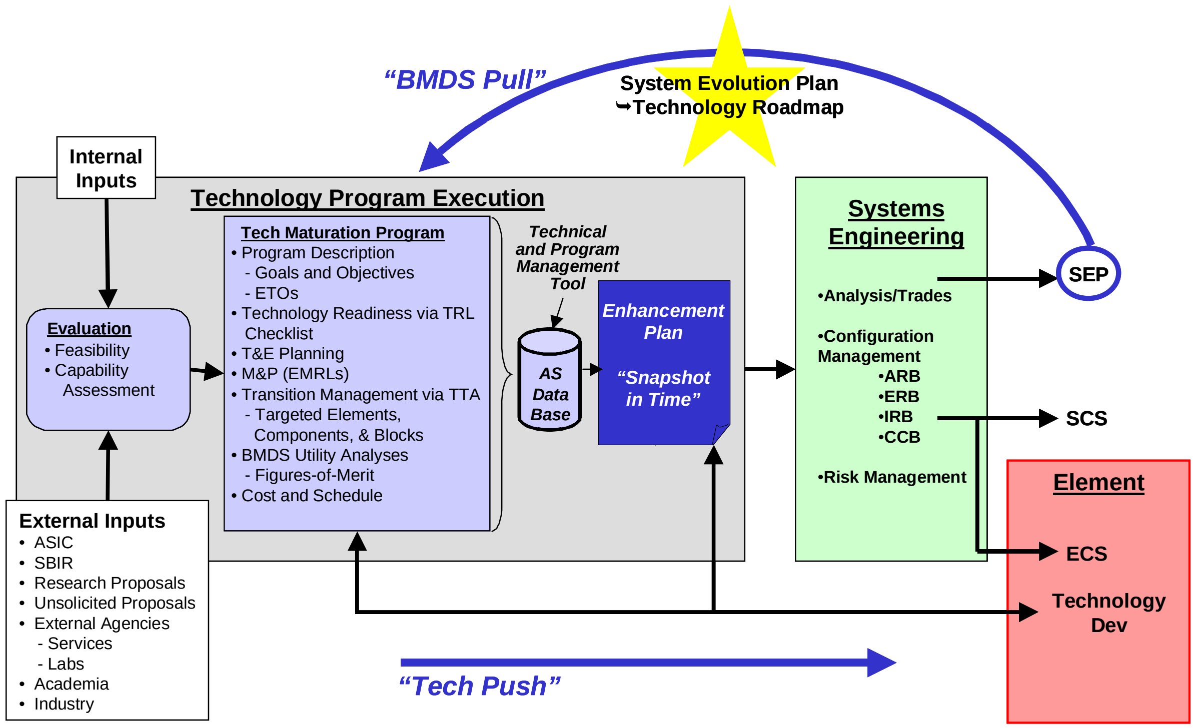

Figure I-2 MDA's Technology Development Process
(Source: *BMDS Integrated Program Plan*, 11 June 2003 draft, Figure 22)

MDA/AS should prepare a Strategic S&T Implementation Plan to delineate the interrelationships among the proposed MDA/AS future-oriented S&T activities and other aspects of MDA R&D management, such as systems engineering, mission analysis, and systems architecture planning. That plan would need to include a clear and agreed statement of the MDA/AS mission because it concerns long-term S&T and innovation, beyond currently planned BMDS systems. The plan should include resource commitments and authorities, and it should articulate the types of S&T strategies that will be pursued and key processes to be employed. The chapters that follow describe several types of recommended strategies and processes that MDA can adapt to its particular needs.

II. PROMOTING RADICAL INNOVATION IN MDA

Michael J. Lippitz and Robert C. Wolcott

OVERVIEW

MDA's mission objective is to "develop and field an integrated BMDS capable of providing a layered defense for the homeland, deployed forces, friends, and allies against ballistic missiles of all ranges in all phases of flight."[1] This mission raises broad and complex challenges. In addition to standard engineering and technology development work, addressing these challenges will require significant innovation over the next few decades. MDA/AS has been charged with, among other things, developing innovative systems and concepts to the point where MDA leadership can make informed decisions about transitioning them into formal development programs.[2]

This chapter outlines three types of recommended efforts: (1) seeking, refining and developing new concepts to meet various mission needs; (2) proving out promising solution concepts to the point where senior MDA management can reach an informed decision about whether to transition them into a formal development program; (3) supporting emerging technologies that could facilitate breakthrough improvements in missile defense systems, subsystems, or key components, and in doing so enable revolutionary approaches to fundamental missile defense challenges.

PROBLEM DESCRIPTION

The term "innovation" implies the development of a new product or process that entails a departure from existing approaches. The terms "disruptive innovation" or "radical innovation" have been used to denote technologies that are implemented in ways that foster profound changes in operations or strategy, as opposed to an "incremental" innovation that solves a narrower problem—often cost or feature improvements—not

1 *http://www.acq.osd.mil/bmdo/bmdolink/html/mission.html.*

2 "MDA examines the widest possible range of options, potentially inserting enhancements at all levels of the BMDS…including evaluating innovative approaches, paradigm shifts, and new concepts…." *BMDS Integrated Program Plan* (11 June 2003), "Advanced Systems" section.

requiring significant adjustments in methods or approaches. [3] Radical innovation has been defined in terms of the type of new performance enabled, that is, embodying one or more of the following:

- New to the world performance features.
- 5–10 times (or greater) performance improvement.
- 30–50% (or greater) reduction in cost.[4]

Radical innovations are characterized by high levels of not only technical and market uncertainty, as has been the traditional definition, but also high levels of organizational and resource uncertainty. Organizational uncertainties refer to the ability of a project team to overcome various forms of internal barriers to radical change. Resource uncertainties refer to problems in obtaining the necessary funding and competencies to carry radical innovation projects forward.[5] Indeed, a common theme in the history of radical innovation is that the originator of the innovation is often not the same organization that eventually exploits the innovation for significant gain. Xerox is infamous for inventing but not exploiting several radical innovations in the modern personal computer industry, such as the graphical user interface, the first word processing program, and the laser printer.[6]

The radical innovation problem could be considered at three levels in MDA:

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3 The concept of a disruptive technology/innovation can be traced back to Joseph Schumpeter's *Capitalism, Socialism and Democracy* (1942). Schumpeter describes capitalist economies as engines of "creative destruction" in which new firms adopt disruptive innovations that challenge existing firms' dominance. His concept was based on recognition that long-term profitability in a competitive environment depended on creating market inefficiencies that could then be exploited. Successful firms make above average profits over time by constantly innovating, that is, by constantly disrupting the market. More recently, the term "disruptive technology" was popularized in Clayton Christensen, *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail* (Harvard Business School Press, 1997). He defines disruptive technologies as ones that "bring to the market a very different value proposition than had been available previously." Geoffrey Moore uses the term "discontinuous innovation" in *Crossing the Chasm* (Harper Business, 1991) to refer to "products that require us to change our current mode of behavior or to modify other products and services."

4 Richard Leifer, Christopher M. McDermott, Gina C. O'Connor, Lois S. Peters, Mark Rice, and Robert W. Veryzer, *Radical Innovation: How Mature Companies can Outsmart Upstarts*, (Boston: Harvard Business School Press, 2000).

5 John Doerr of Kleiner, Perkins, Caufield & Byers, one of the most successful and respected venture capitalists in history, identifies four types of risk similar to those addressed by Leifer et al. Doerr considers financial, technology, market, and organization risk in any venture investment decision. Mitigation of these risks continues to guide the venture development process after investment. Doerr's approach to risk reflects that of most technology venture firms, though some venture firms are more successful at managing these risks than others.

6 R. C. Alexander and D. K. Smith, *Fumbling the Future: The Story of Xerox and Personal Computing* (New York: Morrow, 1988).

- Developing missile defense capabilities that have never existed before.
- Enabling leap-ahead performance or cost improvements in missile defense components.
- Seeking and supporting revolutionary technologies and "disruptive capabilities," that is, transformations in operations and strategy typically (but not always) enabled by synergistic combinations of technologies.

Current MDA programs are focused almost exclusively on employing proven technologies to implement concepts that are believed to be achievable within a few years. The initial system being deployed at Fort Greeley, Alaska, is seen as the beginning of a spiral development program in which future capabilities will be built up through incremental improvements in system components, as well as the introduction of new, independent layers of defense. Because current missile defense capabilities are "rudimentary,"[7] any future-oriented MDA program is aiming to create something that has never existed. Future layers are contemplating leap-ahead improvements in critical components (e.g., much more powerful and cost-effective lasers).

Our focus here will be on the conception, selection, management, and transition of MDA programs aimed at fostering revolutionary technologies and disruptive capabilities exceeding what can be achieved through incremental improvements of current missile defense approaches. Our previous work for MDA[8] found that encouraging radical innovation requires different management processes and technology competencies than are typically employed in both government and industry S&T[9] programs. In many cases, corporations and government programs would create a separate "organization to support long-term S&T and foster radical innovation that is independent of…project offices, but works with them for implementation."[10] For consistency, the structures and processes described in this chapter will adopt the framework in Chapter I, in which an MDA innovation organization would operate as an independent group headed by a Chief Innovation Executive but embedded within the overall MDA S&T program under the MDA/AS. However, these functions could be implemented in other ways. The manner and extent of an innovation group's integration within MDA would depend on the details

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7 Secretary of Defense Donald Rumsfeld, Ronald Reagan Public Policy Briefing, 12 October 2003, http://www.defenselink.mil/transcripts/2003/tr20031010-secdef0752.html.

8 Van Atta et al, *Science and Technology*.

9 "Science and technology" is the U.S. government terminology for what in the commercial world is typically called research and development (R&D).

10 Van Atta et al, *Science and Technology*, p. ES-2.

of current MDA organizations and processes, as well as on MDA leadership priorities. Although these issues were not engaged in detail by this study, certain general implementation issues are discussed in the following section.

MDA IMPLEMENTATION ENVIRONMENT

A successful missile defense system will consist of a complex, integrated "system of systems" in which multiple layers of integration will be required. Building such a system of systems entails large-scale engineering work that requires solving thousands of problems involving tradeoffs among technical properties, manufacturing limitations and costs, and customer values. That engineering work will typically reveal gaps in the system concept requiring adjustment of subsystem specifications, interfaces, and performance margins. Sometimes the process will also reveal gaps in basic technologies and even scientific understandings. This is particularly true in the missile defense domain, where the speed and energy of certain phenomena present problems well beyond the state of the art in key technologies; in some cases, the underlying physics may not be thoroughly understood.

Scientific and engineering approaches to missile defense trace back to antiaircraft systems developed during and after World War II. The United States built a variety of missile defense systems during those years, culminating in the Safeguard System, which was eventually deactivated in 1976. Meanwhile, the DEFENDER Program, begun by the Advanced Research Projects Agency in 1959, was the beginning of a series of scientific and engineering projects focused on understanding and measuring the basic phenomenology of missile launch, ballistic flight, and atmospheric reentry.[11] The MDA of today is the latest incarnation in a series of high-level management organizations created since 1983 within OSD and intended to focus overall Department of Defense (DoD) efforts to build missile defenses.

OSD missile defense organizations have varied significantly over the years with changes in the perceived threat environment and differing emphases and priorities of different administrations. This history is relevant to the innovation problem to the extent that it has created *(1) a set of missile defense concepts, technologies, and science* that have been investigated to various levels; *(2) experienced personnel* and centers of excellence, mostly outside of MDA; and *(3) expectations about future needs* and

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11 Richard Van Atta and Jack Nunn, "DEFENDER—Science and Technology for Ballistic Missile Defense," Chapter XI in Van Atta et al., *Science and Technology*.

priorities, given that the missile defense problem will never be completely "solved." Adversaries will respond to U.S. missile defense developments, presenting an ever-changing series of threats and challenges. Moreover, the time required to develop and deploy a robust missile defense capability is much longer than the tenure of any given administration.

The Bush Administration made clear its intention to deploy national missile defenses. The United States gave notice on 13 December 2001 that it would withdraw from the Anti-Ballistic Missile Treaty,[12] and on 2 January 2002, the Secretary of Defense signed a memorandum creating MDA with a charge to "field elements of the overall BMDS as soon as practicable." Consistent with this charge, MDA has been focused on deployment of a BMDS with limited capabilities, with relatively few resources for or attention to longer term, innovative approaches[13] or accessing independent technology identification and assessment.[14] (Various outside groups—most notably the Defense Science Board—have continued to examine BMDS technologies and propose alternative system concepts.) Although MDA's adoption of a spiral development philosophy has created a focus on incremental improvements, MDA planning documents call for encouragement of innovation, and some processes appear to be in place to support it.[15]

IMPLEMENTATION OVERVIEW

Design Principles

The essence of innovation is the conception, refinement and realization of "new combinations…something newly tried."[16] In the case of technology-based innovation, an unmet or under-met market/mission need is linked (combined) with a set of technologies that satisfies an important part of the need. For MDA, mission needs are subtasks (e.g., launch detection) aimed at meeting broad missile defense challenges (e.g., boost phase defeat). Promoting innovation in MDA will require three types of efforts: *(1) seeking, refining and developing new concepts* to meet various mission needs; *(2) proving out*

12 "President Discusses National Missile Defense," http://www.whitehouse.gov/news/releases/2001/12/20011213-4.html.

13 Randy Barrett, "Critics Question MDA's Interest in New Technology," *Space News*, 3 February 2003.

14 Randy Barrett, "Pentagon Backpedals on Schedule for Space-Based Missile Interceptors," *Space News*, 7 July 2003.

15 *BMDS Integrated Program Plan*, 11 June 2003.

16 J. A. Schumpeter, *The Theory of Economic Development* (Cambridge, MA: Harvard University Press, 1934).

promising solution concepts to the point where senior MDA management can reach an informed decision about whether to transition them into a formal development program; and *(3) supporting emerging technologies* that could facilitate breakthrough improvements in missile defense systems, subsystems, or key components and in doing so enable revolutionary approaches to fundamental missile defense challenges.

There are many ways to realize these objectives. In the current implementation environment, the design principles in Figure II-1 guided our articulation of options for MDA. The *strategy principles* mean that innovative technology projects must not be "science for science's sake" but rather technology development aimed at meeting mission objectives. The *structure principles* mean that mechanisms for promoting innovation should draw from many different sources—including sources outside MDA—and be flexible and adaptable to the particular skills and personalities of the individuals involved.[17] The *process principles* mean that, although flexible, the process must also be disciplined so projects are steered toward mission objectives; in other words, it is not about just "casting a thousand seeds" and seeing what grows.[18] Finally, the *implementation principles* mean the process should be implemented in small steps, growing organically as it begins to register successes and gain organizational credibility.

Strategy	Mission Focus Senior Strategic Leadership Alignment with MDA
Structure	Scaleable 'Cell' Structure Cross-functional Teams External Network Focus
Process	Stage-Gate Management Process Explicit Support Processes Process Integration with MDA
Implementation	Phased Implementation Start small and scale up Organic Growth (vs. pre-planned)

Figure II-1. Design Principles for an MDA Innovation Organization

17 Chapter IV discusses various networking and outreach mechanisms appropriate to the MDA context.

18 Chapter V delves in detail into a variety of analytic tools that can facilitate a disciplined project and portfolio management approach.

Process Overview

The envisioned innovation promotion process has two main elements:

- *Initial Concept Creation*—The proposed structures and processes are designed to originate and articulate new concepts by helping people regularly make connections between unmet or undermet mission needs and appropriate technologies or systems. New combinations of mission needs with technologies or systems—concepts—must then be sufficiently refined to be considered as candidate S&T projects. The resulting S&T candidates could be aimed at innovations in enabling subsystems or technologies, or they could be proposals for large-scale projects, building an integrated capability from more mature technologies.
- *Refinement and Development*—Following the initial conception stage, a structured process should be employed to winnow out S&T candidates through increasingly rigorous review.[19] If a project survives to prototype demonstration, it may be considered for transition into either a formal development program (if it is judged to provide sufficient value as an acquired and deployed capability) or a radical innovation technology project (if it represents a potential enabling technology).

These processes must not be rigid or linear. Initial concept creation, an inherently creative process, is often referred to as the "fuzzy front end."[20] However, this term has been used less frequently as researchers and practitioners have come to understand key elements of front end processes.[21] These processes can be systematically encouraged, though not inflexibly controlled. Similarly, during refinement and development, a concept that fails to pass through a particular stage-gate review may be moved back to an earlier stage for development in a different direction. Furthermore, technology stage-gate criteria should not be as demanding as a typical "business case" analysis that would be applied to the development of incremental innovations. The criteria applied at each stage should differ depending on the nature of the uncertainties to be resolved—technical, mission, organizational, and resource—and the anticipated time horizon of the concept

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19 Chapter V provides a detailed discussion of the technology stage gate management process.

20 The term was coined by Preston Smith and Donald Reinertsen, *Developing Products in Half the Time*, (Van Nostrand Reinhold, 1991).

21 Peter A. Koen, Greg M. Ajamian, Scott Boyce, Allen Clamen, Eden Fisher, Stavros Fountoulakis, Albert Johnson, Pushpinder Puri and Rebecca Seiber, "Fuzzy Front End: Effective Methods,Tools and Techniques," in Paul Belliveau, Abbie Griffin, and Stephen Somermeyer (eds.), *The PDMA ToolBook for New Product Development* (John Wiley & Sons, 5 April 2002). See also Jongbae Kim, and David Wilemon, "Focusing the Fuzzy Front-end in New Product Development," *R&D Management*, Vol. 32, pp. 269–279, 2002.

(which has an impact on these uncertainties). For instance, a concept may have clear application in a missile defense system while also presenting significant technical uncertainty. Its refinement path would focus on characterizing and managing this technical uncertainty. If the concept were to transition into a formal project, that project would be managed in a manner typical of technology development programs. Another concept might involve a novel application of well-understood technologies that would, if successful, replace an existing program. Its refinement path would depend on measures aimed at building a constituency to overcome organizational resistance. If successful, the ultimate program would be managed in a manner typical of systems development program.

Appropriate processes can play a critical role in creating or discouraging a "culture" of innovation within an organization. For instance, effective networking regimes with experts external to MDA can help overcome the well-known "not invented here" syndrome—a disposition against externally generated concepts and technologies. Combined with effective incentive regimes, these processes can encourage sensible risk taking as well as enable innovation teams to shelve less promising projects.

Key Functions

The process described above at least five functions that need to be addressed in an organization designed to promote radical innovation:

- Mission needs discovery and definition.
- Concept development and refinement.
- Technology identification and assessment.
- Technology creation.
- Proof-of-concept experimentation and demonstration.

Mission needs discovery and definition

To find useful solutions, it is important to understand which problems present the most daunting challenges, as well as the highest impact opportunities. This requires reasonable flexibility and adaptability, so that the effort to gather needs does not become prematurely wedded to a set of predefined requirements from existing users, making consideration of new approaches difficult. The articulation of needs should lead to brief, overall statements of desired capabilities that have few, if any, technical parameters. Stating needs only in terms of capabilities already known to exist inhibits innovative

concept creation. In general, existing users are not good at thinking beyond their current needs, and performance objectives for programs in current development tend to be stated in the context of existing solutions. The means for accomplishing a particular objective tend to be visualized in terms of improvements to the existing technology or capability, rather than a brand new solution.

Thinking beyond the limits of existing processes and biases requires a particular type of observer. Individuals released from the status quo solution have a much greater opportunity of discovering new solutions, but they also need to know what to be aware of. One effective approach is to restate mission needs in terms of a detailed articulation of subsystem and capability needs, then match these needs with general scientific and technological arenas that might offer solutions. Innovation teams would then have specific needs in mind while investigating emerging S&T. Thinking of needs concurrent with the technology search is critical for effective, sustainable concept development. Needs identification and awareness is a strategy under-exploited by many cutting edge technology development groups, from industry to government and academic labs.

Concept development and refinement

The creative process of concept development is difficult to capture. The essence is fostering *particular types of interactions* between people familiar with needs and applications and those familiar with technologies and capabilities. For example, in the Technology Assessment Pilot Project described briefly in Chapter I, a combination of people experienced with missile defense problems interacted with technologists. Working together, they undertook a systematic, top-down analysis that proceeded from high-level BMDS challenges, to novel operational concepts for addressing these challenges, to systems description (at a high level) that might realize the functions, to technical capabilities that could enable such systems to be built. A number of creativity techniques can be employed to encourage novel thinking from users, suppliers, scientists, and technologists.

Innovative concepts can also arise during the engineering work involved in building a system of systems. Such work will sometimes reveal gaps in basic technologies and even in scientific knowledge. Truly innovative organizations encourage and exploit the interaction between application-oriented system designers and technology-oriented scientists and engineers. Faced with a technical roadblock in systems development, scientists may be called in to search for new information, models, and tools. In doing so, systems assumptions may be challenged and new understanding

generated, leading to consideration of innovative solutions.[22] The original problem is transformed by a deeper understanding of the context, leading to novel solution paths.

Technology identification and assessment

Technology identification and assessment requires going from a general statement of need to one with sufficient definition to provide guidance to those charged with worldwide technology scouting. This means translating a general need to a clearly defined set of key performance parameters required to achieve desired application results. Performance metrics must be defined and documented so that discovered technologies can be adequately assessed relative to mission needs.[23] In the early stages of concept development, performance metrics should be broad, to encourage consideration of a wide range of solutions, as it is rarely possible to know what solutions will become available. As concepts become more defined, performance criteria and metrics should become more specific. At the same time, knowledge of available capabilities influences definitions of objectives. Through an iterative process, definition of mission needs and technology metrics co-evolve.

Technology creation

As part of its innovation process, MDA will not be able to rely solely on technologies developed by others. The development of new concepts will foster ideas for new technology investigations that may diverge from what is being pursued elsewhere, given the unique issues associated with missile defense. The technology creation effort would be focused on funding potentially revolutionary technologies with potential for broad application to missile defense challenges, but that are too immature to be linked to specific top-down requirements of a single program. U.S. Government experience with commercial technology programs in the past decade has demonstrated that to access and leverage certain emerging technology developments, MDA will need to monitor and shape these technologies in the early stages.[24] As an example, during the 1970s, DARPA’s steady, forward-looking promotion of critical technologies—before their national security significance became clear—supported U.S. dominance of entirely new

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22 Interview with Bradley Hartfield, 10 June 2002.

23 This same type of refinement is important for the management of long-term strategic technologies, as described in Chapter IV.

24 *Report of the Defense Science Board Task Force on the Technology Capabilities of Non-DoD Providers* (Washington, D.C.: Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, June 2000).

industries, the technologies from which underlay the superior capabilities of many current U.S. military systems.[25] Chapter IV discusses various ways for MDA to structuring collaborative research programs with other government entities, commercial companies, and university programs.

Proof-of-concept experimentation and demonstration

Some concepts will evolve to the point where they can be prototyped to demonstrate concept feasibility in increasingly realistic application environments. Demonstration is often a critical prerequisite to garnering sufficient political support for what can be relatively expensive development efforts. Before such demonstrations, significant system-of-systems integration work must be accomplished, including complex experimentation and assessments. As such, S&T organizations need to employ careful selection, planning, and budgeting mechanisms for demonstrations. Different personnel and management capabilities are required for large-scale integration and experimentation projects than are used for exploratory concept development and refinement. The scale and scope of such experiments can drain resources from earlier stage exploratory S&T. Further, projects that have progressed to this stage will engender the interests of defense contractors, inviting use of the political maneuvering to affect choices.

These basic functions—needs discovery, concept development, technology assessment, technology creation, and system integration/experimentation—suggest the need for various supporting processes, including:

- *Networking and outreach*—Chapter IV discusses various networking and outreach mechanisms appropriate to the MDA context.
- *Project and process management*—Beyond leadership, new concept development, as with any development project, requires documentation, coordination, and measured bureaucratic control.
- *Overall portfolio coordination and leadership*—As the number of innovation projects increases, direction will become increasingly important, especially to ensure that sufficient efforts are devoted to higher risk, higher-payoff efforts.

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25 Richard Van Atta and Michael Lippitz, *Transformation as Transition: DARPA's Role in Fostering an Emerging Revolution in Military Affairs*, IDA Paper P-3698 (Alexandria, Va.: Institute for Defense Analyses, April 2003).

Team Composition

As suggested above, innovative concepts typically arise as applications-oriented and technology-oriented people converge on mutually interesting problems in a process that draws upon both types of skills and temperament. Well-designed processes enable people to be vastly more effective and create a productive "culture" of innovation within an organization. However, no process can overcome poor staffing, particularly if team members' skills and dispositions are poorly matched to innovation tasks. Even good people can be kept from accomplishing their objectives by inadequate leadership and insufficient contact with their broader communities of practice.[26]

Innovation leadership is of particular importance for accessing resources, motivating players inside and outside a team, integrating divergent views, and interacting with senior executives. Innovation leaders—hereafter referred to as "Concept Managers"—must be able to articulate the promise of a concept and be respected enough technically to garner top-level support. Such highly skilled, synthetic thinkers are a rare breed, as are top executives open minded and courageous enough to facilitate them. In the specialized MDA community, it may be particularly difficult to find individuals who have sufficient experience in missile defense to be technically credible while also exhibiting such entrepreneurial qualities. Even if MDA had such individuals, it would still gain from the perspectives of outside talent. As a result, a portion of those recruited as Concept Managers should be from outside the current MDA environment. Ultimately, the MDA innovation program should find a balance between internal "veterans" and external individuals, each with an appropriate combination of technological expertise and innovation capabilities.

An organizational strategy encouraging both internal and external networking and collaboration nurtures the evolution of an innovative organization.[27] An innovation team engaged with external knowledge sources and collaborators will be much more likely to be exposed to new approaches to problems. MDA innovation management should support the search for the best sources for applicable knowledge wherever it resides. It should also work to develop and promulgate shared understandings of alternative system architectures and the particular challenges that flow from them—that is, a common

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26 Alistair Cockburn, "Agile Software Development 2: The People Factor," http://alistair.cockburn.us/crystal/articles/asdpf/asd2peoplefactor.htm (accessed 10 November 2003).

27 See Chapter IV for further discussion of networking and outreach mechanisms appropriate to the MDA context.

language to express “grand challenges.” Shared understandings are important for the conception of innovative solutions in missile defense, given the high level of systems integration required.

A PHASED IMPLEMENTATION APPROACH

Activities aimed at promoting innovation can be implemented by MDA in limited, scalable phases, beginning with a small staff that could grow as promising concepts arise. For descriptive purposes, the growth process is separated into four conceptual phases.

Phase 1	Concept Managers
Phase 2	Supported Concept Managers
Phase 3	Supported Concept Managers with Infrastructure
Phase 4	The Application/Technology Matrix Organization

Review of Phased Implementation of Concept Development

The four phases described above envision MDA concept-development activities growing from a small set of individuals responsible for all aspects of the innovation promotion process, to a formal, matrixed application and technology organization akin to what is found in some well-established industrial organizations. The idea, depicted Figure II-2, is to grow organically, from individual Concept Managers to cross-functional interacting teams of applications-focused and technology-focused people. Because functions will not be rigidly defined, personnel can move easily among roles and share ideas across teams.

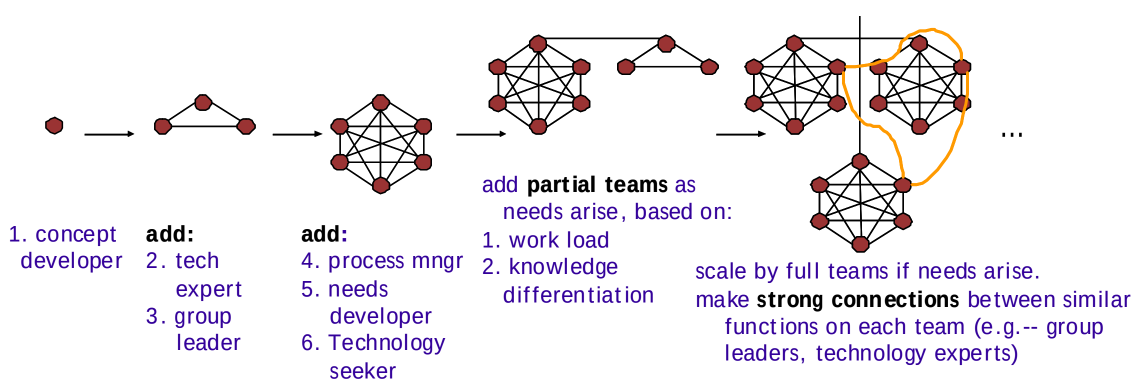

Figure II-2. The Evolution of Innovation Teams and Other Internal Networks

The growth path will depend on the skills, dispositions, and interests of the people involved. For the purposes of discussion, particular functions and support processes are described as though they were the domain of individual specialists, but this may not be the case. Individuals tend to complement and reinforce each other, with specialization evolving naturally based on the strengths and weaknesses of particular team members. Executive leadership and support includes composing and developing effective cross-functional teams.

Phase 1 Implementation: Concept Managers

Concept development is the core of the innovation promotion process. New concepts arise in many ways and can encompass enabling technologies, innovations in subsystems, or broad new approaches to fundamental missile defense challenges. At minimum, an organization can enhance new concept development by protecting and facilitating the highly skilled, synthetic thinkers who generate new ideas. Concept Managers would focus on developing solution concepts, bringing together technologists, integrators, and operational experts from a variety of stakeholder organizations, including potential commercial partners. For example, DARPA continually recruits technically skilled people with innovative ideas—and the drive and disposition to make them real. DARPA program managers are conferred independence, responsibility, and accountability and are expected to show results in 3 to 4 years. DARPA is one of the DoD organizations that provides a useful point of comparison because it has been able to implement some of the best practices identified in the first phase study—consistent, long-term support of critical technologies and simultaneous management of top-down and bottom-up concepts.

As a first step, MDA could recruit or designate Concept Managers and provide them with sufficient funds to contract externally (where necessary) for support in mission needs discovery and definition, technology identification and assessment, networking and outreach, and project and process management. Examples of part-time resources that could be useful to a Concept Manager include the following:

- A pool of technical capabilities to provide occasional “bench scientific support” to test out new subsystem and undertake “due diligence” on the technology components of new concepts.

- Experts in scenario building, wargaming, and the like, to help develop innovative approaches to meet strategic needs.[28]
- Analytic expertise—especially modeling and simulation capability—to facilitate early, inexpensive testing of critical parts of new concepts.
- Technology forecasting experts (mostly outside MDA to avoid potential perceived conflicts of interest).

In addition, many management consulting firms provide services to clients explicitly designed to facilitate creative new concept development, through personnel creativity training, the creation of new organizational environments, outside design specialist services, and process analyses.[29]

Concept Managers could be recruited from among the large group of people with government missile defense experience, as well as the technical experts at national laboratories and academia with relevant applications background. Concept Managers must be technically capable to provide credible leadership and contributions in the eyes of technologists. An insufficient technical aptitude will impede the leader's ability to pose the right questions. The leader's reputation and capabilities must also confer credibility on the innovation team.

The success of this model depends to a large degree on the insight and imagination of Concept Managers, the coherence of the strategic direction from senior leadership, and the Concept Managers' ability to integrate the potential "customer's" mission needs into project direction. Absent strategic direction and appropriate (though light-handed) oversight, this approach can devolve into a "cast a thousand seeds" enterprise. Hence, as suggested in Chapter I, a Chief Innovation Executive should be appointed or designated to oversee the work of MDA Concept Managers.

Phase 2 Implementation: Supported Concept Managers

As Phase 1 effort gains credibility—or if MDA decides to take a more aggressive initial approach—MDA could add additional Concept Managers and provide internal support staff or a stable outsourced capability to help them identify and recognize

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28 The development of detailed scenarios can be particularly important for refining technology needs. See, for instance, R. Van Atta and M. Lippitz, *Transition and Transformation: DARPA's Role in Fostering the Emerging Revolution in Military Affairs, Volume I—Overall Assessment*, IDA Paper P-3698 (Alexandria, Va.: Institute for Defense Analyses, April 2003).

29 Martin Hyatt, *Metaphoric Models of Creative Thinking*, Ph.D. Dissertation, Stanford University Department of Management Science and Engineering, 1999.

opportunities, as well as encourage recruitment of new Concept Managers. These support staff or external capabilities would systematically pursue mission needs discovery and definition, provide continuous technology monitoring and assessment, build and maintain a network of technical and application expertise relevant to MDA strategic challenges, perform regular outreach in important technology communities, and provide professional support for project and process management. Concept managers and support staff could form into cross-functional teams with complementary skills and dispositions (with specialization arising and evolving naturally, based on the strengths and weaknesses of particular members).

Recent research suggests that Concept Managers would benefit from two particular types of support: (1) "hunters," who actively seek out ideas with application potential, and (2) "gatherers," who understand strategic needs and are poised to recognize and technically validate promising new ideas.[30]

> [Hunters are people with] technical training, but they are more likely to be experienced in marketing or business development (in an industrial environment) or in high-level systems management (in government). Perhaps more importantly, a successful hunter knows how to articulate the opportunity in compelling terms that gain the attention of higher management—something that few bench scientists are skilled at doing…[Gatherers, on the other hand,] have the technical sophistication to assess what they encounter. In addition, their life experiences have engendered a certain…awareness of markets and social and scientific trends…first-line and midlevel research managers and senior scientists (often play) the role of gatherer.[31]

In the MDA context, hunters could be thought of as "Mission Analysts." The key skills involved are (1) perceptive listening, (2) a talent for seeing through immediate problems to broader needs, and (3) the ability to delineate needs from multiple perspectives and in sufficient detail to provide guidance to technologists and developers. They would likely come from within MDA staff or a government laboratory. Operational experts who understand current applications and Service cultures could help focus teams on areas likely to have value for end users.

Senior technologists could serve as gatherers. Ideally, these are respected, well-connected people with a reputation as contributors to missile defense or related applications. They would be network builders, who would provide access to technical

30 Leifer et al., *Radical Innovation*.
31 Ibid. p. II-15.

evaluators, and attract top talent to participate on innovation teams. These players could come out of program offices or laboratories. A related support function would be “Technology Scouts.” These are experts in technology search who vigorously pursue learning about new technologies and their possibilities. People with this orientation are hard to find. They are similar in many respects to Concept Managers, but without necessarily possessing the requisite leadership and management skills. These players can be important contributors to concept development and refinement, as well as technology forecasting.

By this phase, it will be important to begin formalizing the technology stage-gate process for project evaluation. The stage-gates must be defined to assess projects in terms of strategic fit; potential impact; and technical, mission, organizational, and resource risks. One of the most important metrics should be “learning per dollar.”[32] That is, how can evaluations be accomplished efficiently, to bring focus to the most promising ideas (and shelving of others for future consideration)? Assessment of strategic fit would include consideration of MDA, OSD, and Service objectives, as well as synergies and conflicts with existing programs. A conflict would not necessarily eliminate a project from consideration but would suggest the need for different types of management. The stage-gate process itself would need to be developed by a cross-functional team with a variety of experience, and tested against some past or present sample projects for practicality.[33]

The support functions outlined here are only illustrative of useful capabilities in an innovation team. Not all of these functions would necessarily need to be staffed. One would expect team members to play multiple roles at different times, depending on team composition, concept evolution, and leadership priorities. Innovation teams could have as few as two people or as many as half a dozen or more, depending on the complexity of the concept. It would be the responsibility of the Chief Innovation Officer to identify talent and drive innovation team composition.

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32 Mark Rice, project review meeting, 24 June 2003.

33 Chapter V delves in detail into a variety of analytic tools that can facilitate a disciplined project and portfolio management approach, including a specific example of a potential MDA technology stage-gate process.

Phase 3 Implementation: Supported Concept Managers with Infrastructure

As good ideas develop, MDA could further enhance concept development efforts by providing some formal tools and standard processes, primarily to support networking and move projects toward acquisition.

For instance, a "Network Manager" could work with Concept Managers to develop and maintain contact and communications with external expertise, to encourage and support the development of "communities of practice." Experts tend to gravitate toward individuals with similar knowledge and interests. Professional networks develop trust and awareness between individuals, allowing members to quickly identify and consult with appropriate experts more efficiently and successfully, all of which are critical to concept development. A community of practice also provides forums for ongoing online and offline interactions between experts within and across organizations. They enable host entities, from individuals and academic institutions to firms and government organizations, to efficiently access expertise for meeting specific objectives and ongoing talent development.

Active network development can greatly facilitate concept development; absent such a network, significant time and energy would be required to identify and mobilize expertise for each new concept. Many industries, such as telecommunications, software, and semiconductors, combine the efforts of multiple firms and organizations into technology development consortia to accomplish common objectives, such as standards development. The coordinative and networking functions of technology consortia often require active, professional management, with many organized as separate corporations with full-time management teams. Venture capital firms employ full-time people to identify external resources capable of adding value to new ventures and investment selection. Simply organizing professional meetings can require significant effort.[34]

Similarly, a specialist "Process Manager" could support Concept Managers and others in meeting stage-gate approvals and funding requirements. The Process Manager could also supervise a small information technology support staff charged with installing, populating, maintaining, and mining of a knowledge base of MDA S&T programs and innovation concepts, that is, an information system providing electronic repository of "organizational memory." Organizational memory facilitates concept development by

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34 Chapter IV discusses various networking and outreach mechanisms appropriate to the MDA context.

retaining innovative ideas with potential to add value in the future, perhaps when a particular technology matures.

Figure II-3 depicts the evolving structure of the innovation team. Technology expertise and applications expertise interact with networking and process support, under the direction of a Concept Manager or the Chief Innovation Executive. Again, this depiction is illustrative. Innovation teams would not have to follow a strict structure. A single individual could undertake more than one role, or two individuals could share a role, depending on the specific needs of the concept under development. The form and internal functions of a team will depend on the skills and dispositions of its members. Furthermore, an early stage project might be refined by a “core team” of two or three people, with other people added as the concept evolves. However, clearer team structure enables the Chief Innovation Executive to recruit for particular skills, based on emerging areas of need.

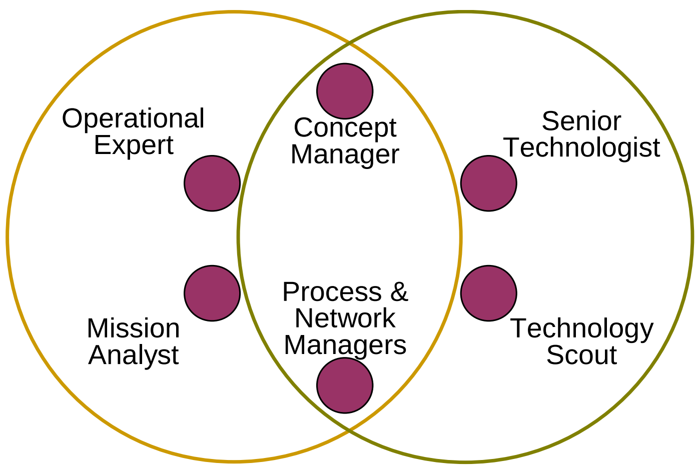

Figure II-3. Basic Structure of an Innovation Team, with Representative Roles

As MDA innovation activities achieve respect and acceptance, the group could establish more formal relationships with external providers of the types of variable resources identified in Phase 1, with expanded duties as suggested below:

- Members of the pool of technical capabilities could serve on evaluation boards and provide bench scientific support and due diligence on the technology aspects of new concepts. For MDA, whose systems are often specialized and whose perspective spans decades, the “pool” may also serve as a source of new technologies that underlie new concepts, as well as an important repository of organizational memory.
- Experts in scenario building, wargaming, and assessment could supervise external concept and scenario development exercises, in addition to supporting

innovation teams. Experts from think tanks could undertake longer term innovation studies.[35]

- The modeling and simulation capability could be expanded and potentially internalized as a "center of excellence."

Also, the technology stage-gate processes might require further formalization. Mechanisms must encourage the timely termination of unpromising projects, focusing support on higher potential projects.[36] Evaluation boards that implement the technology stage-gate should also provide support for concept refinement. One option would be to form an independent expert group, populated with external technologists, former senior R&D managers, military planners, and experienced innovation project managers. This group would, where appropriate, be offered as a resource to Concept Managers.

Finally, a high-level "Innovation Board" could be formed to decide when a concept was ready to become a formal prototype or demonstration project. Because movement through this gate will generally require more substantial budgetary and technology resources, such a board should include MDA executives and independent outsiders.

Phase 4 Implementation: The Application/Technology Matrix Organization

The pool of technical capabilities from which Concept Managers would draw should properly reside in an organization that supports the professional development, networking, and refreshment of internal technical talent. Because MDA does not have significant independent technology identification and assessment capabilities, these people will likely come from contractor, DoD, and Department of Energy labs. In the future, if MDA S&T investment increases, MDA technology resources could be organized into a virtual lab, perhaps in the form of different external labs serving as organizational homes for various strategic technologies. A virtual lab offers several mechanisms for addressing the critical issue of intellectual property and facilitates sharing. Chapter III describes the concept and benefits of a virtual lab.

Our concern here is not with the details of how technologists supporting MDA would be organized but rather how these technologists would be brought into regular

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35 For example, a study explaining how pursuing breakthrough technologies and innovative concepts is compatible with "spiral development."

36 One of the key factors in constructively ending a project is to encourage its people to redeploy into surviving projects—not just by assigning them, but rather by finding ways for them to buy into the new assignment. One way to facilitate this process is to include the staff in the downselect process.

contact with members of MDA's innovation teams. In Phase 3 development, interaction with technologists is likely to be mostly ad hoc and project based. In Phase 4, "Application Teams" focused on different aspects of the ballistic missile defense problem (e.g., tracking, hard target kill, etc.) could be formed to provide continuous focus on particular common issues and encourage cross-fertilization across concept development efforts. Then, if some form of internally controlled technical pool develops, applications teams could be put in a matrix with various strategic technology groups to make their interactions more regular. In other words, technologists, who naturally organize themselves along lines of technical expertise (e.g., electro-optics, fluid dynamics, engineered materials, etc.) would be brought in to serve on particular Application Teams. Figure II-4 highlights the roles of application teams and technology groups.

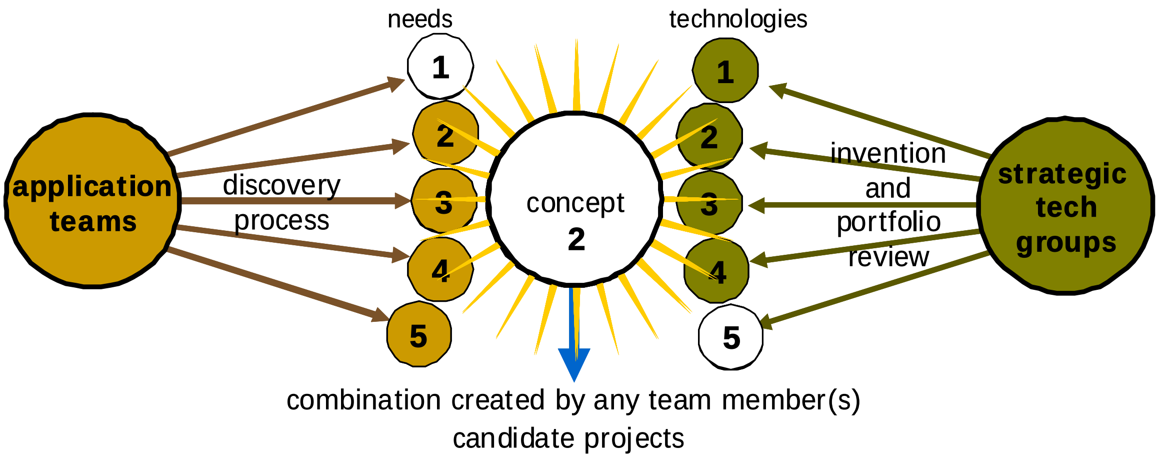

Figure II-4. Interacting Application Teams and Core Technology Groups Foster New Concepts

Prototyping and Demonstration

"The person who proposes a new idea is rarely the best one to be put in charge of carrying it out, for the gifts of conception and of execution do not commonly reside in the same personality." —Sydney J. Harris

Over time, some projects will become ready for prototyping, systems-level experimentation, and demonstration. As suggested earlier, these projects should be managed separately from concept-development activities. Financially, separating prototyping and demonstration from initial concept development isolates these relatively expensive projects to avoid diverting resources from long-term S&T investment. Culturally and managerially, building operating systems is a very different process from early research. Concept development is visionary: a wide-ranging process aimed at

discovering new approaches to problems. Conversely, prototyping and demonstration should be focused on closure: refining the known, making tradeoffs, and implementing as yet imperfect solutions in the near term.

MDA/AS could, if deemed advantageous, form an Advanced Experimentation Office that focuses on proof-of-concept demonstration. Though the management process would differ, selected members of the project teams could transition along with the projects, to convey commitment and institutional memory, as well as maintain contact with the group of people behind the original concept. Contact with the original concept-development team will help address challenges arising during the prototyping and experimentation phase.[37]

An Advanced Experimentation Office could evolve as concepts are approved for conceptual and physical prototyping as a result of the stage-gate process. The need for mechanisms for prototyping and demonstration will become evident as projects mature. Given their disruptive nature and resource requirements, resistance may arise from existing programs. Prototyping and demonstration will provide leadership with evidence to address such resistance (or show it to be valid). Explicit support from top MDA leadership will be crucial to carry a program into true experimentation—that is able to sustain setbacks without risk of immediate cancellation—especially when this experimentation is costly.[38]

If an Advanced Experimentation Office exists, it can take responsibility for other efforts that support innovation but are not specific to particular concepts or projects. For example, it could take responsibility for developing a center of excellence in MDA modeling and simulation, as suggested above, to minimize experimentation costs. This center of excellence would be a mechanism through which the Advanced

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[37] Continuity will also be important if, in the process of turning a project into a program, difficulties arise that argue for returning the concept to a previous stage for further refinement before undertaking more proof-of-concept experimentation.

[38] This problem is not unique to DoD. Potentially disruptive new products often fail in the commercial arena because they threaten established, profitable product lines. At an early stage of development, it is often unclear whether the new product will be received favorably by customers, many of whom may be new customers. (Like DoD, business must often “create customers” for innovative new products.) The high start-up costs associated with launching a new product mean that it will generally be a near-term drain on company profits. For disruptive products, achieving profitability may take even longer. If they are forced to compete against near-term profit or asset utilization criteria set by incumbent business areas, they may die before ever being able to demonstrate their market potential. In enlightened companies, various mechanisms are employed to foster and shield innovative developments from pressure exerted by their established product lines. Innovations that are not exploited by the developing firm often migrate to competitors, who use them to capture market share from the originators.

Experimentation Office obtains early insight into emerging concepts. It could also incubate proven systems capabilities as they find operational niches. The key idea is to keep a new capability focused on a limited application area, iteratively enhancing it through experimentation. Effective experimentation should enable the emerging capability to confront increasingly challenging missions until it is sufficiently mature, reliable, and supportable enough to meet the demands of acquisition, testing, and evaluation organizations. Figure II-5 below represents the process.[39]

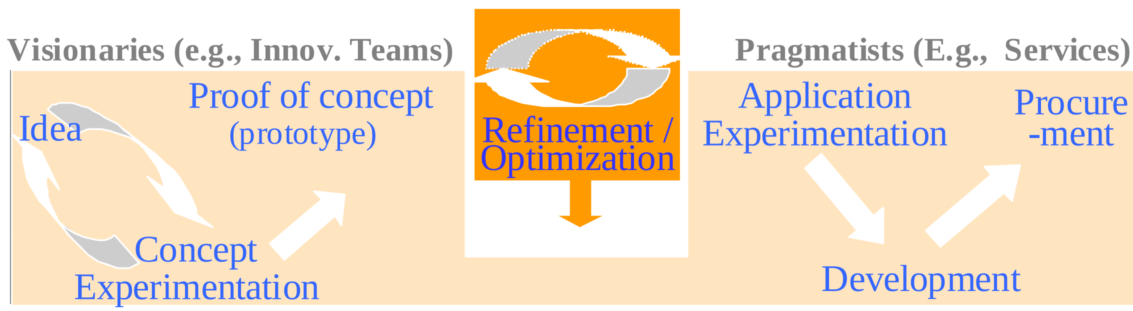

Figure II-5. Incubation Can Fill the Gap between Prototype Development and Initial Application

Transition to Formal Development Programs

MDA/AS does not control the acquisition and deployment of new capabilities. Because its ideas may challenge existing programs and bureaucracies, it may be difficult to find eager customers. Many innovation projects will not transition to acquisition and deployment in a direct manner. The path from R&D to new missile defense capability is likely to be complex and nonlinear, involving numerous players inside and outside government. Long delays may exist between proof-of-concept and exploitation. As such, *if fielded disruptive capabilities are the objective, it will be insufficient to generate an example and then rely upon the traditional DoD/Service acquisition system to recognize its value and implement it.*

This becomes clear during the prototyping and demonstration phase. Because new capabilities generally lack technical maturity or operational robustness, the traditional DoD program-development process will be reluctant to undertake the risk-reduction

39 Van Atta et al., *Science and Technology*.

efforts required to move them into acquisition.[40] Rapid acquisition and deployment of disruptive capabilities require an integrated senior leadership effort, from the Director of MDA and Under Secretary for Acquisition, Technology and Logistics. OSD leaders must also have allies among top Service leadership to alter the course of ordinary organizational politics. These individuals must exercise authority to overcome organizational resistance to new ideas, uncertainty, and perceived competition.[41] Whenever possible, transition to formal development programs should be accomplished while those who brokered the initial deal are still in power.

RECOMMENDATIONS

In addition to refinement of the options presented herein, the primary issues to be resolved relate to MDA's specific organizational priorities, capabilities, and readiness to implement the recommendations below. The first few measures would be implemented immediately, while the others could evolve over time as successful early stage projects emerge.

- *Appointment of a Chief Innovation Officer*—This person would lead and support the overall effort, overseeing Concept Managers and providing funds to contract for support in mission needs discovery and definition, technology identification and assessment, networking and outreach, and project and process management. In the near term, we estimate that *funding on the order of $10 million would be sufficient to begin supporting innovation processes in MDA.*
- *Recruitment of Concept Managers*—These managers would create, refine and develop innovative concepts. Concept Managers could be recruited from among the extensive group of people with missile defense or related experience. *MDA could successfully begin its innovation promotion activities with about six or so Concept Managers.*
- *Formation of innovation teams*—These teams would be formed through both internal and outsourced support for Concept Managers. These terms could be made up of technology scouts who are experts in rapid technology search and early concept conception; mission analysts who have talent for seeing through immediate problems to broader needs and are capable of recognizing and technically validating promising ideas; and operational experts who understand current applications and customer cultures. *This enhanced organization could*

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40 R. Van Atta and M. Lippitz, *Transition and Transformation: DARPA's Role in Fostering the Emerging Revolution in Military Affairs,Volume I—Overall Assessment*, IDA Paper P-3698, (Alexandria, Va.: Institute for Defense Analyses, April 2003).

41 Ibid.

consist of something like 20 staff and a budget on the order of $20 million, though the staff could be smaller and the budget larger depending on the extent of support activity outsourcing. Moreover, it will be important to distribute early funding authority to prevent a single individual from killing an idea in its early stages.

- *Implementation of formal tools and standard processes*—These processes could include a "technology stage gate" process for winnowing out S&T candidates through increasingly rigorous review; an independent expert group; a high-level "Innovation Board" to decide when a concept is ready to become a formal prototype or demonstration project; a "Network Manager" to develop and support "communities of practice"; a "Process Manager" to manage DoD bureaucratic and budget requirements; a small information technology support staff charged with installing, populating, maintaining, upgrading, and mining a knowledge base of MDA S&T programs and innovation concepts.
- *Creation of mechanisms for regular interaction with technologists*—"Application Teams" could be formed to provide continuous focus on certain common missile defense issues and encourage cross-fertilization across concept-development efforts. Such teams could help focus technical experts from various disciplines toward ongoing concept development in terms of mission needs and application requirements, rather than in terms of technology specializations.
- *Formation of an Advanced Experimentation Office*—This office would focus on proof-of-concept experimentation and prototype demonstration. Early on, this would take the form of a planning function that anticipates implementation issues of maturing concepts. When projects are ready for prototyping and demonstration, they should be managed separately from concept-development activities because of the differing nature of the work and higher costs.

III. STRATEGIC TECHNOLOGY STEERING & EXECUTION

Lee Kindberg and Marius Vassiliou

OVERVIEW

Strategic technology steering refers to mechanisms useful for high-level management of a portfolio of long-term S&T projects in a limited number of technology areas deemed critical to the long-term success of the MDA mission. This chapter outlines the strategic technology steering concept and suggests ways MDA could implement elements in the near term, without significant organizational change, while laying a basis for an expanded effort linked to a long-range S&T steering and execution strategy. It concludes with a discussion of the use of virtual laboratory mechanisms for executing S&T in strategic technology areas, including a way of involving S&T contractors consistent with MDA organizational capabilities, needs, and outlook, as well as legal and regulatory constraints.

THE ORGANIZATIONAL TECHNOLOGY STEERING PROBLEM

Technology steering is intended to focus resources and management attention on those critical few technologies that have long-term strategic impact on the success of the organization's overall mission.[1] The intent is to maximize S&T productivity, effectiveness, and timeliness in these technologies—often designated as "key," "core," or "strategic" technologies, the terminology we have adopted here. Effective technology steering mechanisms must address a number of organizational needs, both from a management perspective and at the technologist level, including resource allocation mechanisms, management tools, internal and external technical communications and collaborations, technology scouting systems, and development and stewardship of technical personnel. Ideally, technology steering is a component of an integrated S&T strategy that also includes idea generation and transition to operating divisions for use or deployment.

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1 "Critical few" refers to the quality management concept described by Dr. W. E. Deming and others that organizations must identify and focus on the critical few issues or problems most likely to have significant impact, distinguishing them from the "trivial many" problems facing any manager.

Technology Steering approaches should be designed to be long-term in vision and time frame, yet sufficiently flexible to meet changing organizational needs, mission targets, and management priorities. These approaches must be structured to weather organizational restructurings and changing management personalities, and still adapt to meet the organization's needs in that time frame and environment; at times, these approaches must respond to address immediate challenges. These approaches and tools often lead to the development or expansion of new technical competencies in the organization.

THE MDA IMPLEMENTATION ENVIRONMENT

The missile defense mission has evolved over the years and taken on new aspects in the most recent reorganization to form MDA. While technology has been critical to mission success throughout the organization's existence, organizational structure and resources committed to long-term S&T have varied. This has likely contributed to personnel turnover in long-term technical roles and a possible loss of organizational memory. With leadership movement between MDA and other DoD organizations and with military personnel promotion systems that create turnover, leadership tenure has also tended to be short when compared to the private sector. At present, MDA is focused on implementation, with longer term S&T de-emphasized. No formal long-range MDA Strategic Technology Steering function currently exists, though a recent draft Integrated Program Plan identifies the need for "frequent close coordination between MDA/AS and Element Program Directors…to ensure all technology areas identified in the Technology Roadmap are pursued…." (See Figure I-2)

Adapting commercial models to MDA will often not be straightforward because of MDA's contract research environment and federal regulations governing contractor participation on advisory bodies. In addition, selecting the right initial leader and team will be critical to successful implementation. MDA may not currently have the ideal mix of personnel to initiate implementation of a vigorous long-term S&T program, or if present, they may be assigned to more immediate programs. MDA's history of organizational change may make it difficult to attract and retain the long-range S&T personnel needed, so time and creative approaches may be required to research staffing. The discussion of "virtual laboratory" possibilities at the end of this chapter provides possible alternative structures aimed at overcoming these difficulties.

IMPLEMENTATION OPTIONS

A range of options and variations are available to MDA to implement technology steering mechanisms. Technology steering functions in the public- and private-sector cases studied in Phase I ranged from purely technical networks to full technology-management systems covering the total S&T effort. Some managed people and resources, selected technical directions, and articulated the long-term strategy of the organization. Others focused just on specific technologies. All dealt with tracking or driving innovations in targeted areas, often in partnership with key contractors or partners. The following technology steering models were deemed to have strong potential as options for MDA.

Key Technology Steering Groups

A well-defined example of a technology steering process was put in place at ITT in the 1970s by Dr. Charles Herzfeld, a former DARPA director. ITT's Key Technology Steering Groups were established to develop and manage S&T programs in selected priority technology areas. Key Technology Steering Groups determined needs, set objectives, and tracked technical progress, with the intent of focusing and linking the programs to product needs, but they were not involved in the specific day-to-day conduct of individual projects within the thrust. Establishing Key Technology Steering Groups was a function of high-level technology management, as part of the overall technology management process. Key Technology Steering Groups reported to the Chief Scientist (the highest level corporate technical management), who had an active role in research management and regular access to the Chief Executive Officer. Membership included the best domain experts for the technology subject, serious potential users of the technology to be developed, and the main producers of the technology, with outside experts as guests and advisors. The chairs were chosen from the experts in the field.

"Next generation technologies" group established in an existing S&T organization

The DuPont APEX Research Model is a formal process for portfolio and project management as part of DuPont's overall long-term central R&D effort. An APEX Science Board, led by the Chief Science & Technology Officer, oversees Science Boards associated with each of the company's three "strategic platforms." These boards include the highest-level technical leadership and require business unit involvement even at the earliest stages of research. A highly structured three-stage "Technology Stage Gate"

process is used to evaluate projects for resources and inclusion in the next stage of the development portfolio.

Formal collaborative models

Integrated High Performance Turbine Engine Technology Program

The Integrated High Performance Turbine Engine Technology Program (IHPTET) started in the 1980s (and is now transitioning to VAATE, the Versatile Affordable Advanced Turbine Engines Program). IHPTET aimed to bring coherence and encourage collaboration in turbine engine R&D performed by contractors sponsored by the U.S. Air Force. The IHPTET Steering Committee is led by an OSD S&T executive, with membership including all the user communities affected by turbine engine technology [the Services, National Aeronautics and Space Administration (NASA), Department of Energy]. Linking research with applications encourages technology transition and builds user community support for the long-term research program and budget. The Steering Committee oversees an Industry Panel and three types of technology panels: Technology Focus Area Panels, Pervasive Technology Panels, and Technology Application Panels. The focus area panels and specific technology panels function like the Key Technology Steering Groups in the ITT model. Panel members, who represent the teams that actually do the research, are generally not members of the Steering Committee. Because turbine engine technology is mature, IHPTET panels focus on measurable goals and objectives as opposed to new concepts, radical innovations, and quantum improvements in performance.

National Technology Alliance

The National Technology Alliance is a program run by National Geospatial Intelligence Agency to discover, initiate, or accelerate development and exploitation of commercially available solutions to meet technology needs for intelligence applications. The National Technology Alliance (1) acquires knowledge of Government operational user needs by conducting technology needs assessment and analysis; (2) seeks out commercial technology solutions; (3) performs R&D aimed at leveraging commercially developed technology; and (4) provides a forum for exchange of Government technology needs, solutions, and experimentation. The National Technology Alliance funds dual-use R&D projects (1–5 years out) and prototype development in selected technical areas. Technical focuses are determined through a review of published DoD needs statements, a proprietary review process, and input from DoD laboratory representatives. Respondents are consortia of companies and academic centers that respond to a Broad Area

Announcement. Task orders are then issued to consortia to develop specific products, in coordination with agencies and end users. A private organization, the Rosettex Technology & Ventures Group, was created to advance and commercialize technologies of high interest to The National Technology Alliance. Rosettex has a team of more than 60 partners representing major technology consulting firms, established and new companies, independent research institutes, academic institutes, and government contractors. Members of the consortium were chosen so that Rosettex could address the entire time line of technology development up to acquisition. They are divided into groups organized around stages on that time line to eliminate conflicts of interest and so to foster free exchange of technical information at the precompetitive level while protecting intellectual property rights.

Network of interested professionals with Network Executive Committee (Hughes)

Hughes formed voluntary networks of technical professionals in identified critical technology areas, each of which was led by a Network Executive Committee (essentially a Key Technology Steering Group of 6–12 representatives from each business group involved). Each representative was a person with a technical background and good experience in the subject technology, who also controled resources. Typical members might be laboratory managers (heading engineering organizations of 100–300 people) or chief scientists or engineers. The “control of resources” qualification might mean line control, program control, or simply control through influence and respect. This approach has the advantages of addressing both the management and steering needs (top down) and the technologists’ needs for interaction and communications (bottom up).

A STRATEGIC TECHNOLOGY STEERING GROUP FOR MDA

A Strategic Technology Steering Group should be long-range and strategic in view, structure, and membership. These functions are intended to “guide” new exploratory research in areas of particular importance to the organization. Thus, for MDA, Strategic Technology Steering Groups would focus on technologies critical to long-term systems and future-generation strategic needs, beyond currently planned blocks upgrades and spanning multiple blocks. To be most effective, technology steering leadership should have knowledge of the strategic technology and its mission implications, ties to the leading practitioners of that technology, and authority to commit resources. Common characteristics of successful Strategic Technology Steering Groups include the following:

- High-level support, visibility and engagement.
- The groups offer long-term technical leadership and active oversight for a particular S&T thrust of particular importance to the organization, but they are not involved in day-to-day management of individual projects.
- Chairs of particular Strategic Technology Steering Groups are acknowledged experts in a technical community directly relevant to the thrust area.
- Membership emphasizes expertise and competence, not position, and includes the best domain experts for the technology and serious potential users of the technology to be developed. Membership may include the main producers of the technology, and it should include outside experts as guests and advisors.
- Steering group meetings meet regularly—initially once per month, moving to 2–3 month intervals. The meetings are at places where the S&T work is done (research facility or contractor's location). The sessions should be closed and discussions classified or confidential.
- They must act as and become teams, not just committees.
- They must be structured to weather short-term organizational changes.

Organizations often transition into a Strategic Technology Steering Group structure by starting with a small pilot or prototype to demonstrate and fine tune the concept, which then is applied to additional technology areas. Successful concepts are often adopted by other parts of the organization. Table III-1 gives a menu of components from which MDA can build an initial prototype and then expand it as organizational needs are defined or the environment becomes more receptive. While some clarification of the menu options is required, the primary issues to be resolved relate to MDA's specific organizational priorities, capability, and readiness to implement these measures. It will then be possible to select a target technology for the prototype Strategic Technology Steering Group and further define the necessary structures.

Table III-1. Prototype Components and Options

Organizational Need	Strategic Technology Steering Group Prototype Components and Implementation Steps
Technology Steering	1. Identify technology for first implementation. (Link to MDA Technology Roadmap and strategic planning processes.) 2. Establish Strategic Technology Steering Group focused on that technology. • Respected leader assigned at the 25–50% effort level. • Members from MDA/AS and other MDA elements for which this technology is critical (essential to success) • Identified top management sponsor/champion, who must be committed, engaged, and kept informed. • Connection to technology resources outside MDA (options below). • Responsible for tracking and reporting on technology, prioritizing efforts, identifying unfilled needs, evaluating new proposals, and output of “Innovation Hub.” • Provide substantial input to future Technology Roadmaps and strategic plans. 3. Support with voluntary networking of related technology community (see below). 4. With growth, expand structure both up and down, following the IHPTET model: • Add additional Strategic Technology Steering Groups as critical technologies are identified. • With multiple Strategic Technology Steering Groups in place, implement an MDA Technology Council as (1) an oversight board to prioritize and direct the long-term efforts and as (2) stewards of the Technology Roadmap and these critical long-range technology thrusts.
High level support	1. Executive sponsor or direct reporting relationship for Strategic Technology Steering Group. 2. Strategic Technology Steering Group participation by key element program leaders. 3. Commitment to provide strong Strategic Technology Steering Group leader(s) and member(s). 4. Clear definition of expectations for communication to upper management. (These areas are critical for success.)
Coordinate efforts across MDA (to communicate needs and develop support)	A Hughes-style Strategic Technology Network would enhance the capability of the Strategic Technology Steering Group to identify and meet needs, prevent duplication of effort, and encourage collaboration. (Networking is addressed further in Chapter IV.)
Engage user community	The IHPTET Steering Committee included representatives from all key DoD stakeholders. Depending on the technology(ies) selected, the structure established should accommodate inclusion of both internal and other DoD experts and users. A planned series of long-range S&T symposiums (limited attendance?) would showcase and communicate new concepts and needs, provide recognition for strong contributors and innovators, and increase interaction across the organization and support community.
Track and engage outside technology expertise	1. The IHPTET Industry Panel model would allow participation by contractor personnel with critical knowledge while complying with legal requirements on contractors serving on advisory bodies. This participation could vary in roles, levels, and duration and include participants who are not long-term “members” of the team. 2. If interactions are to extend to R&D organizations beyond the typical DoD contractors, a CBRTA-type coalition contracting structure would allow pre-competitive interaction of companies on critical R&D while protecting intellectual property rights and expediting contracting. This could be established most expeditiously as an additional “BIN” under the National Technology Alliance umbrella.
Tools for advancing projects and allocating resources	Implement a modified technology stage-gate process similar to the DuPont APEX structure, with modifications to address MDA’s mission specifics, longer time horizon, and contract environment.

VIRTUAL LABORATORIES FOR EXECUTION OF STRATEGIC S&T

As the strategic technology steering framework comes into being, MDA could benefit from developing more formal structures for executing S&T programs in strategic

technology areas. This section describes how MDA could create a close-knit collaborative structure with expert organizations in various areas to create a virtual laboratory.[2]

What is a Virtual Laboratory?

In recent years, the outsourcing of research has been occurring at an increasing pace in a wide variety of industries, both to decrease costs and to gain access to unique capabilities present elsewhere.[3] A virtual laboratory is a highly collaborative form of outsourcing, with significant integration of the various organizations involved and joint management processes of considerable breadth and authority. The involvement of the central organization in the execution and management of the research, and the depth of commitment of the various partners, is such that the collaboration looks almost as if everyone belonged to the same research organization.

A virtual laboratory occupies the middle ground between performing research in-house on the one hand and simply issuing research contracts to external organizations on the other (see Figure III-1). Consider first the right side of Figure III-1. To the far right are in-house research organizations, of which there have been a number throughout the last 40 years. Xerox's Palo Alto Research Center, Hewlett-Packard Laboratories, and IBM Thomas J. Watson Research Center are among many examples, as are some National Laboratories. Moving left in the figure, we encounter more complex R&D organizations, with geographically distributed laboratories (nationally or internationally). The global research organizations of Sony and Matsushita are examples of these, as is Boeing's Phantom Works.[4] Notwithstanding the increased complexity, these are not virtual laboratories by our definition. They are geographically distributed research organizations affiliated with the same parent organization.

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2 M. G. Russell, "The 'Virtual Laboratory': Alliances for Technology Transfer," *Proc. Twenty-Seventh Annual Hawaii International Conference on System Sciences*, 1994, pp. 478–482.

3 S. J. Kobrin, J. T. Battenberg, P. Hewitt, P. J. Jennings, J. Joerres, S. Kumar, F. Mer, "Worldsourcing's Next Frontier: R&D," World Economic Forum Annual Meeting, Davos, Switzerland, 2004; C. H. Kimzey and S. Kurokawa (2002), "Technology Outsourcing in the U. S. and Japan," *Research and Technology Management*, Jul.–Aug. 2002, pp. 36–42; R. Varma, "Changing Research Cultures in U.S. Industry," *Science, Technology, and Human Values* 25, 2000, pp. 395–416; A. H. Rubenstein, "Coping with Downsizing and Outsourcing: The Virtual Corporate Research Lab," *Proc. Portland International Conference on Technology and Innovation Management (PICMET 99)* v. 2, 1999, pp. 434–437.

4 S. Arimura, "How Matsushita Electric and Sony Manage Global R&D," *Research and Technology Management*, Mar-Apr 1999, pp. 41-52; J. Fricker, "Boeing's Phantom Works: Shaping the Future," www.aviationnow.com, 18 June 2001.

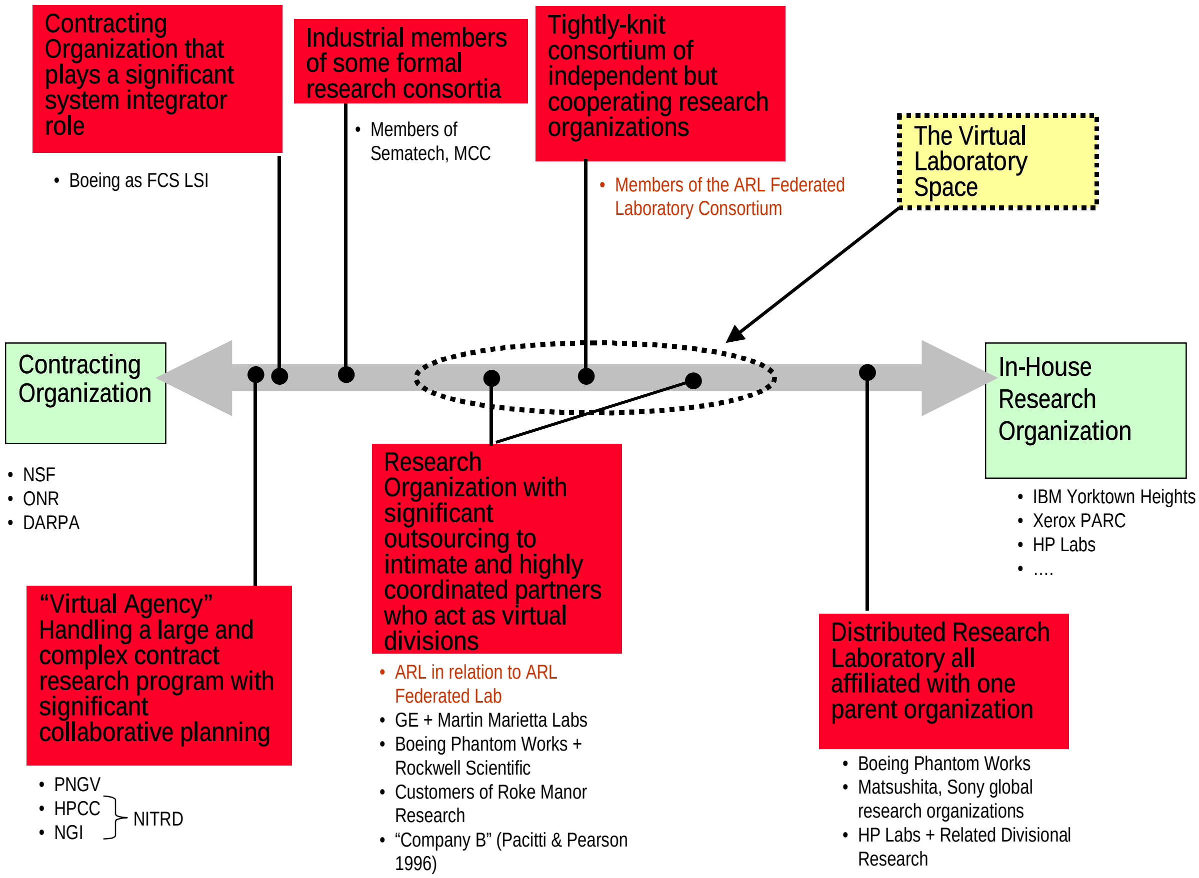

Figure III-1. The Virtual Laboratory Continuum

Consider now the left side of Figure III-1. To the far left are contracting organizations such as the National Science Foundation, the Office of Naval Research, and DARPA. Despite the intelligence and creativity of the contract monitors and program managers at such institutions, their mission is not to perform original research internally, but rather to let contracts to external organizations. These external organizations execute the contracts with varying levels of guidance and report their results. In some cases, the involvement of the contracting organization increases. This entails a move away from the left end of the figure and toward the center. There are collaborations among government agencies for large and complex contract research programs, which can be thought of as "virtual agencies."[5] Examples of large programs managed by virtual agencies include the

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5 M. Castro, R. S. Foster, K. Gunn, and E. R. Roberts, "Managing R&D Alliances Within Government: The 'Virtual Agency' Concept," *IEEE Transactions on Engineering Management* 50, 2003, pp. 297-306.

Partnership for a New Generation Vehicle,[6] the High Performance Computing and Communications program, and the Next-Generation Internet. These virtual agencies engage in significant and activist collaborative planning, but they are merely complex contracting organizations, not virtual laboratories. Only as a contracting organization becomes more involved in the actual execution of the contracts it lets does the assembled enterprise take on more of the character of a virtual laboratory.

In the center of the figure is the virtual laboratory space, designated by the dashed oval. The coordination and commitment of the partnerships here are at a maximum, as is the incremental management overhead associated with the collaborations. Some virtual laboratories are formed when research organizations undertake significant outsourcing to partners, with whom there is very close coordination. These partnerships often involve personnel representing the contracting organization spending significant amounts of time and energy working with partner organization personnel. For example, Pacitti and Pearson describe the case of a large electronics company which they call Company B. This company, after severely downsizing its central R&D laboratory, rebuilt its research infrastructure in a completely distributed fashion, with small local laboratories all over the world. Some of these laboratories are internal to the company, and some are external. Here, a significant amount of central direction and planning is balanced with local autonomy. The entire assemblage appears to constitute an effectively functioning virtual laboratory.[7] Another example is the relationship of Martin Marietta laboratories with General Electric in the wake of the sale of GE's aerospace business to Martin Marietta (later part of Lockheed Martin).[8] A similar relationship is that of Rockwell Scientific with Boeing Phantom Works after the sale of Rockwell's aerospace divisions to Boeing. Rockwell Scientific has functioned as a virtual division of Phantom Works for the last 8 years. (This case is discussed in more detail in Appendix A.)

The Army Research Laboratory's (ARL) Advanced Displays Federated Laboratory is particularly relevant to MDA because it was led by a government research laboratory. The Advanced Displays Federated Laboratory comprised a tightly knit collaborating consortium of industrial and academic research institutions led by ARL in

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6 National Academy of Sciences, *Review of the Research Program of the Partnership for a New Generation of Vehicles: Seventh Report*, National Academy Press, 2001.

7 B. Pacitti, and A. Pearson, "Organizational Networks in R&D," *Proc. International Conference on Engineering and Technology Management (IEMC 96)*, 1996, pp. 428-433.

8 United States General Accounting Office, *Defense Restructuring Costs: Projected and Actual Savings from Martin Marietta Acquisition of GE Aerospace*, Letter Report, 09/05/96, GAO/NSIAD-96-191.

the pursuit of common goals. The ARL Advanced Displays Federated Laboratory is also discussed in detail in Appendix A.

Implications for MDA

A virtual laboratory structure may provide MDA with a viable method of accessing talent and capabilities that would be very difficult or impossible to assemble and retain at any cost. A virtual laboratory would also allow for arrangements that are more flexible and with fewer human resource constraints than if all capabilities were maintained in-house, while allowing for better understanding, control and coordination than simple contracting. On the other hand, a virtual laboratory involves higher management overhead, less flexibility, and higher cost than pure contracting, at least in the near term. Conflicts of interest between the institutions making up the virtual laboratory divisions must also be managed. Experience suggests that a number of factors associated with successful virtual laboratories could be implemented for MDA:

- Consistent, stable, multiyear funding for the enterprise. There must be an incentive for external organizations to invest the time and effort to become virtual divisions.
- A dedicated Virtual Lab manager at the contracting agency (likely MDA/AS) and a dedicated leader at the designated prime external organization. Both individuals must be energetic champions and must have real and widely recognized authority.
- Dedicated local managers and staff at each virtual division.
- Highly knowledgeable active researchers at MDA/AS to engage with virtual divisions.
- Some coordinated control of incentives (personnel evaluations and compensation).
- Unambiguous agreement among virtual divisions to let work be centrally directed.
- Collaborative planning with significant input from virtual divisions.
- Arbitration mechanisms to handle conflicts of interest.
- Staff rotation in and out of MDA/AS and between virtual divisions.

CONCLUSION

This chapter has outlined principles and methods for management and execution of strategic missile defense technologies. Specific implementation steps over time could include the following:

- Establishing a Strategic Technology Steering Group focused on a selected technology with a respected leader and, critically, direct reporting to supportive, committed top management.
- Supporting the Strategic Technology Steering Group with networking of related technology communities, potentially including industry panels created to allow contractor participation.
- Implementing a technology stage-gate process with modifications to address MDA's mission specifics, longer time horizon, and contract environment.
- Developing virtual laboratories to perform long-term S&T, that is, a highly collaborative form of S&T outsourcing employing formal, precompetitive coalition contracting structures to permit interaction of companies on S&T while protecting intellectual property rights.

IV. NETWORKING AND OUTREACH FOR MDA SCIENCE AND TECHNOLOGY

Daniel Petonito

INTRODUCTION

This chapter describes a phased implementation plan for best practices in internal and external networking and outreach. Networking and outreach are different functions with different objectives. Networking is primarily about processes used to interact with the scientific community to identify promising technologies, potential emerging threats, gaps in current research, and partnering opportunities. It has an external aspect, aimed at obtaining independent evaluations, and an internal aspect, aimed at improving coordination on the MDA research agenda. Outreach has more of a customer relations aspect. While it can be directed to the scientific community, it will more often be directed toward the leadership of MDA and its major programs elements (“the Elements”). The primary function of outreach is to maintain support for a healthy long-term research program by explaining and demonstrating the value of long-term research in supporting the MDA mission.

IMPLEMENTATION ENVIRONMENT

Networking and outreach are critical parts of a long-term S&T program. A review of case studies from previous research for MDA[1] identified five key attributes that networking and outreach can support. These attributes were present in organizations with a successful long-term S&T program. Table IV-1 shows the key attributes and specific functions identified. Each is discussed in turn.

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1 Van Atta et al., *Science and Technology*.

Table IV-1. Key S&T Performance Attributes Supported by Networking and Outreach

	IBM	Chrysler	Corning	AT&T	Dupont	Sun	Rockwell	GE	Polaris	Atlas	Night Vision	Turbines	Nuclear Sub
Maintain Support for SIT Program													
Maintain Top management Support	X	X	X	X	X	X	X	X	X	X	X	X	X
Organizational Leader Directly Involved in S&T Decisions	X		X		X	X	X			X			X
Validate Program to Management & Outside Stakeholders	X				X		X	X	X	X	X	X	
Connect Research with Strategic Objectives													
Create Bold Visions and Mission Statements	X				X	X						X	X
Identify Key/Core Technologies	X		X	X	X	X							X
Link S&T to Strategic Objectives - Reassess Periodically	X		X	X	X	X		X			X		X
Create Technology Plan or Roadmap	X		X			X			X			X	X
Establish Steering and/or Technology Committees	X				X		X	X	X			X	X
Support Near-term Development													
Link S&T Program Including Project ID with Divisions	X	X	X	X	X		X	X	X	X	X	X	X
Create Joint Projects with Product Divisions	X						X	X					
Provide Technical Problem Solving Capability	X		X	X	X	X	X	X	X	X	X	X	X
Identify Gaps, Common Needs and Exploit Synergy					X	X	X	X			X		X
Understand the Needs of the User	X	X			X		X	X			X		
Seek and Obtain Outside Technical Advice & Technologies													
Conduct University Research Program	X	X			X			X					X
Seek and Obtain Technology & Technical Advice	X	X			X	X		X	X	X	X		X
Form Outside Advisory Committee for Independent Review					X				X	X			
Keep Abreast of Scientific Achievements around the World	X					X		X			X		X
Establish Partnerships with Tech Leaders Worldwide													
Establish Partnerships with Technology Leaders	X	X	X		X	X		X		X		X	
Conduct University Research program	X	X			X			X					

Maintain Support for S&T Program—An attribute shared by the organizations studied was the need to gain and maintain support within the organization for a long-term research program. This support must come from the highest levels in the organization. In industry, this translates to the Chief Executive Officer and the Corporate Board, which together are directly involved in S&T decisions and actively support a strong research program. Support from the development groups in industry or the Elements in MDA is also important to maintain a strong, long-term S&T program. This is especially true during budget resource allocation decisions. If the Elements have not seen or received value from long-term research, their support for the program is unlikely. Mechanisms to

provide strong and continued support for a long-term S&T program will have to be part of the overall implementation strategy.

Connect Research with Strategic Objectives—One of the first ways to gain support for a long-term S&T program is to connect it to the strategic objectives of the organization. Without this connection, it will be difficult to show how long-term S&T is providing value to the organization or to maintain support for a healthy program. To ensure this connection, oversight and decision-making for a long-term S&T program will have to come from top MDA executives.

Support Near-term Development—The primary reason to support the Elements is to help the organization achieve its mission. A primary benefit of this support is that it demonstrates the value of a long-term S&T program. It does not appear that mechanisms are in place in MDA to allow MDA/AS to provide this support to the program Elements. Mechanisms to link the research being conducted with work underway in the Elements and involving them in the long-term S&T program will have to be established. At the same time, Element involvement must not divert too much funding away from the long-term S&T objectives. Continued support for a long-term S&T program from upper management and portfolio management that commits funding to long-term research will help prevent this.

Seek and Obtain Outside Technical Advice and Technologies—MDA must be able to take advantage of the advice of technical experts, as well as technological advances taking place throughout the DoD, other government agencies, domestic industry, and ultimately the world. For this to happen, mechanisms must be in place to keep MDA informed of technological advances, and a network has to be established with other technology leaders that would allow MDA to take advantage of technologies that can help meet its mission. In addition, mechanisms to incorporate those technologies into future MDA systems must also be established.

Establish Partnerships with Technology Leaders Worldwide—Partnering with other technology developers is a method of networking and sharing the cost of research, accelerating the advancement of technologies, and steering technology developments to meet a specific MDA application.

In addition, internal communications is critical for project identification and selection, transition of technology, and maintaining support for a long-term S&T program from both MDA leadership and the Elements. Formal and informal mechanisms to

increase the flow of information to the Elements and MDA Leadership must be established if a healthy long-term S&T program is going to be maintained in MDA.

Table IV-2 and Table IV-3 list specific networking and outreach mechanisms identified through the case studies. Those that best fit MDA and how they can be applied are discussed in the next section.

Table IV-2. Networking Mechanisms

NETWORKING MECHANISMS	
External	Internal
SEARCH	COMMUNICATE
• Identify and use of other organizations' technology, including government labs.	• Facilitate participation of business unit personnel in central research programs.
• Hunters and gathers seek out and promote the use of external concepts and technologies.	• Have Chief Technology Officer/Chief S&T officer sit on corporate board.
• Locate labs near important intellectual centers.	• Corporate Executive Council sets S&T strategy through annual process.
• Have Chief Scientist maintain liaison with scientific community.	• Assign personnel to select customers or PM offices.
• Conduct "Idea safaris" to elicit ideas.	• Reassign individuals between R&D to assist in transition.
• Visit laboratories around the world.	• Hold annual internal technical conference(s).
• Conduct brainstorming sessions with top scientists.	• Hold seminars and educational programs.
• Review university research, scholarship, or intern programs.	• Create an internal Web site for research to collaborate on new ideas.
• Prepare focused Broad Agency Announcements.	• Use cross-disciplinary teams, Peer-to-peer virtual networking, and regular meetings to discuss problems and progress.
• Use business units to help collect technologies.	• Use an advocacy program at small business units to be consultants and to bring ideas back.
EVALUATE	EVALUATE
• Continually assess competitors' technologies.	• Establish strategic technology advisor committee.
• Evaluate intelligence reports.	• Establish technology assessment/oversight/evaluation groups.
• Establish technical/scientific advisory panels.	• Poll engineers annually on technology needs to identify gaps.
• Conduct technology gap assessments.	• Establish ad-hoc technical review group.
• Hold annual S&T conference—These should be technically oriented.	• Co-locate S&T with small business units when possible to enhance communications.
EXECUTE	GUIDE
• Partnering/Teaming.	• Involve development groups in S&T management.
• Share cost of research across organizations.	• Develop road maps to identify gaps and overlaps and to determine where to focus S&T.
• Establish alliances between university research and commercial firms.	• Tie S&T to corporate strategy.
• Have joint projects with customers.	• Use senior S&T managers/researchers as liaison to business units.
• Spend time in the field to experience problems faced by the troops.	• Have technology steering groups.
• Have temporary exchanges of technical personnel among DoD and industry labs.	• Share ideas across business units.
• Establish Centers of Excellence in key technologies.	• Identify projects with development groups to solve today's problems and meet future needs.
	• Create a Component Improvement Program that is funded to correct problems identified by business units.
	• Build close relationships with PMs to determine near- and long-term needs and to help it shape its S&T program to meet needs of customers.
	• Small business units provide part of central research funding and tell them what they need done. Details worked through negotiation.

NETWORKING MECHANISMS	
External	Internal
	• Central research should work with customers to identify 100 plus key objectives at beginning of year that formed basis for funding. • Do cost sharing/partnering with development groups. • Focus on transition of technology to development groups. • Form cross-functional teams—Commodity Management Approach.

Table IV-3. Outreach Mechanisms

OUTREACH MECHANISMS	
External	Internal
• Host annual S&T conferences that are technically oriented.	• Maintain top level support.
• Review technical journals.	• Ensure a close, continuing relationship between the Chief Executive Officer and Chief Technology Officer.
• Obtain support of leading scientists in the nation and fund their ideas.	• Ensure that Technical director maintains influence over course of all R&D.
• Provide validation of scientific reasonableness to public, administration, and congress.	• Science Center director is required to provide regular “State of Science” reports to the Board.
• Attract best and brightest scientists to maintain interest and participation from scientific community.	• Maintain product division support.
• Offer continual field demonstrations for Congress, headquarters, and users.	• Head of Science Center personally represents the Center to the operating divisions at the highest possible level.
• Closely cooperate with Army staff and field commanders.	• Solve business unit problems to demonstrate importance of central R&D.
• Lead and actively participate in meetings and conferences.	• Science Center must be viewed as an important asset.
• Have temporary exchanges of technical personnel among Army, DoD, and industry labs.	• Hold corporate technical conferences.
• Spend time in the field to experience problems faced by troops.	• Use metrics to measure small business unit and central research performance.
• Support outside publications.	• Establish metrics for projects and overall program.
• Get out and spend time with customers, users, scientists, and government.	• Review technical effectiveness of business units to determine S&T resource allocation.
	• Small business units grade corporate research and development annually on whether it is meeting key objectives.
	• Document and advertise successes in organization.
	• Create internal journals, (e.g., *Science at Rockwell*).

IMPLEMENTATION

Implementing the changes required to establish a centrally controlled long-term S&T program in MDA will be difficult because of the organization’s current focus on fielding an initial missile defense capability. The approach being proposed is to lay out the long-term goals and start with some initial steps that can be taken to initiate the process. This will require the strong support from MDA leadership and will likely be met with resistance from the Elements. However, including the Elements in the process and minimizing resource requirements in the early years may reduce this resistance. In addition, showing early success (without a sacrificing long-term focus) will demonstrate value to the organization.

Outlined below are recommended steps for MDA/AS to establish internal and external networking and outreach processes to support the establishment of a long-term S&T program in MDA. These initial steps begin to put into place many of the key attributes discussed above. In combination with the management initiatives previously discussed, these steps will help establish a long-term S&T program in MDA/AS that, with some initial successes and the continued support of MDA's leadership, can grow. The plan outlined below is intend to be implemented over a 3-year period and includes the initial steps that could be taken to:

- Sustain support for a long-term S&T program from MDA's Command Group and establish mechanisms to link and involve the Elements in process.
- Seek and obtain technical advice from outside sources.
- Keep abreast of advances in strategic technologies.
- Establish partnerships with technology leaders outside MDA.
- Support innovative promotion.

Sustain Support for a Long-term S&T Program

The primary initial focus should be on development and communication of top management support. MDA/AS should brief the Director and senior MDA leadership on proposed plans for strengthening the long-term research program in MDA and obtain their approval. That approval should come in the form of a memorandum from the Director of MDA to the Elements that does the following:

- Provides a commitment from the Director to strengthen the long-term research program in MDA, establish the initial framework for the program, and lay out the initial steps that will be taken.
- Establishes an S&T Management Board and Corporate Oversight Board to manage the program.
- Establishes funding goals and a portfolio approach for the long-term research program to allow resources to be committed to long-term research (10-plus years) while providing support for the organization's more immediate needs.
- Directs Elements to identify members for an S&T Management Board and work with MDA/AS to recommend a research agenda and strategic technologies that should be supported and funded by a central research program.
- Directs that the Corporate Oversight Board be briefed within 4 months on the proposed central research agenda and on how S&T Management Board will continue to support a strong, centrally funded research program.

Once this management structure is approved, networking and outreach activities should be initiated to facilitate the exchange of information in MDA about the S&T program and to maintain continued support for the program. We suggest two initial activities:

Annual MDA S&T Conference—This would be a 1- or 2-day conference for MDA and its contractors. The primary purpose of the conference would be an exchange of information about the various S&T activities underway; it would also provide an opportunity to identify potential areas of cooperation and minimize duplication of effort. The conference would facilitate transition by increasing (1) the awareness of research underway in MDA, (2) the identification of new applications, and (3) the potential redirection of research. In addition to presentations from MDA/AS on the current S&T program, the conference would include presentations from the Elements on their current activities as well as their technology needs. The extent of industry participation is something that would have to be worked out with MDA, but at a minimum they should be allowed to have exhibits.

Quarterly Technology Seminars—These would be half-day seminars with the primary purpose being an exchange of information on current research in a specific technology area—more than likely one of the strategic technologies being pursued by MDA/AS. Although the focus of the presentations would be on MDA/AS activities in the technology area, presentations could also be made by other DoD or government agencies, as well as the Elements, industry members, or academics.

Additional activities that could begin sequentially or concurrently, depending on resources, are (1) developing an intranet for MDA to capture and make available the principal results and data from the S&T activities underway in MDA and (2) establishing periodic meetings between the director of MDA/AS and the Element heads to review current S&T activities underway supporting the Elements, issues or problems, and research priorities. The importance of meeting with the Elements to discuss issues and review priorities was highlighted in several of the Phase I case studies. We recommend beginning during the third year because there will already have been significant interchange during the first two years to establish the program and the initial research agenda.

Seek and Obtain Technical Advice from Outside Sources

MDA/AS should seek the advice of outside experts to validate its research agenda, explore alternative approaches, and gain support from these experts (who in

some cases will be MDA stakeholders) for MDA's long-term S&T program. Many of the activities described in this chapter will support this objective, but several steps can be taken with this objective specifically in mind.

An initial step would be to establish an S&T Advisory Board of outside experts on ballistic missile defense acquisition, development, and technology, with representatives from government, industry, and academia. The board could meet twice a year to review MDA's current technology challenges and MDA/AS's research agenda and to provide technical advice to the Director of MDA/AS and the Corporate Oversight Board. The S&T Advisory Board would have a core group of members that could be supplemented with technical experts based on the current challenges and technology thrusts being faced by MDA/AS.

Another step would be to establish a Web page for individual strategic technologies. An example is the Web site developed and maintained by the Institute for Defense Analyses to provide cognizance of MEMS technology for DARPA. When combined with other networking activities, a quality Web page that the scientific community can depend on for reliable information on a specific technology can be a valuable tool. Being the host of such a site provides significant advantages and is a valuable step in networking with the scientific community.

Keep Abreast of Advances in Strategic Technologies

A primary function of networking is to remain cognizant of technological advances taking place outside of MDA. It is not practical to attempt to do this for all technologies or even all those that may have an impact on MDA. Instead, we recommend that mechanisms be established to remain cognizant of only a select set of strategic technologies.

First, to provide the technical competency needed to maintain cognizance of the strategic technologies, it may be necessary initially to outsource this activity to a cadre of technical experts from an external S&T organization that will be able to interact with the scientific community worldwide and keep them abreast of technical advances. Second, MDA should investigate the use of a smart search engine that can perform focused searches for specific technologies across government, industry, university, and scientific journal Web sites. Many products on the market can be used, but they have different

levels of sophistication.[2] The actual search function could be performed by and FFRDC (federally funded research and development center) or contractor and the results provided to the MDA/AS staff and any organization or individual providing technical expertise to MDA/AS.

MDA could also hold technology workshops on specific technologies. Although held primarily to identify partnering opportunities, these workshops could also be used to remain cognizant of a technology area. The basic model being suggested are the workshops sponsored by the Air Force's Dual Use S&T Program. These workshops bring together people working in specific technology areas to identify areas of common interest and explore opportunities to work together. Because they are fairly labor intensive activities, holding no more than two in a given year is suggested.

Building on this, MDA could hold its own Missile Defense Strategic Technology conference. This would be an intensive undertaking, but it would facilitate networking with the S&T community and allow MDA to bring together those researchers working on the technologies of most interest to it. The technology workshops discussed above could be an integral part of the conference.

Establish Partnerships with Technology Leaders

Establishing partnerships—jointly funding research projects—is one of the most significant activities that MDA can take to leverage research underway outside of MDA and to leverage available internal S&T funds. Partnerships can be established with other DoD and government organizations and with industry. Before partnerships can be formed, however, a detailed analysis of technology needs has to be accomplished. This analysis has to include the identification of gaps in research, areas of mutual interest, and partnering opportunities.

A first step would be to hold meetings with S&T counterparts in DoD and other government agencies to identify interest and explore opportunities for partnering. These should be held after the strategic technologies have been identified. The purpose of these

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2 They primarily fall into two categories. Inexpensive software that can download vast amounts of data, requiring extensive manpower to sort through and extract those pieces of data needed. These can range in price from less than $100 to several hundred dollars. The second option is more expensive software ($100,000 to $200,000) that performs a more intelligent search, catalogs what has been downloaded, and requires much less manpower to make sense of what has been found. This may be a more logical option for MDA/AS. The initial costs should more than pay for themselves in reduced manpower requirements. In either case, a thorough review of options and a cost-benefit analysis is needed before expending resources on any software to search the Internet.

meetings is to determine interest and to develop an initial plan on how to proceed. A series of meetings may be required to develop the relationships needed to form research partnerships.

Following this, a detailed analysis of each strategic technology will have to be accomplished before any serious partnering discussions can be held. For instance, in the course of the study underlying this report, nanotechnology was selected as technology that may be of interest to MDA, and it served as an example of what could be done for each of MDA's strategic technologies. The analysis of nanotechnology is in Appendix B. It includes the following:

- Current research underway and a list of government organizations performing research in nanotechnology.
- Identification of key research areas of interest for MDA.
- Opportunities for MDA to network with organizations performing research in nanotechnology.
- Specific steps MDA can take to become engaged in nanotechnology research.

The actual analysis of the strategic technologies would have more detail than what was done for nanotechnology, and it should include gap analysis of the research underway at MDA and within the government to determine those areas where MDA may want to fund or form partnerships with. MDA should focus its funding in (1) areas that have the potential of providing significant benefit to MDA that are currently underfunded and (2) those areas being adequately funded but heading in a direction that will not support future MDA needs. Once this analysis is completed for a strategic technology, detailed discussions and technology workshops (discussed in the previous section) can be held with potential partners. The objective of these discussions is to reach a joint funding agreement that includes the level of funding for each partner and specifies who will lead the research effort.

If MDA/AS is going to actively support the Elements, partnerships can also be initiated with the Elements. Activities described above under "Sustain Support for a Long-term S&T Program" would be the initial steps to providing support to the Elements and, where applicable, to forming partnerships with them to fund research projects.

Industry partnerships can also be investigated at the same time. A detailed analysis of needs is still required, but to form industry partnerships, it would also have to be determined whether the technology has commercial potential and, if so, whether MDA would be willing to lose at least partial control of the technology developed. If all

conditions are met, a Broad Agency Announcement could be released for select research efforts in support of the strategic technologies, which possibly would meet the pressing needs of the Elements.

Support Innovation Promotion

The activities described in the preceeding sections will establish the type of organization needed to support a viable long-term research program and foster innovation promotion. In addition, the networking and outreach activities described above will result in a substantial flow of information that will help identify and analyze innovative concepts. Chapter II includes a detailed discussion of networking and outreach in the service of innovation promotion.

CONCLUSION

Active networking with the scientific community inside and outside MDA is crucial to identifying promising technologies, potential emerging threats, gaps in current research, and partnering opportunities. Outreach to these communities and to MDA executive and program leaders will be necessary to gaining support for a healthy long-term research program. This chapter has described numerous steps that can be taken by MDA/AS over the next 3 years to establish internal and external networking and outreach processes to sustain support for a long-term S&T program, seek and obtain technical advice from outside sources, keep abreast of advances in strategic technologies, establish partnerships with technology leaders, and support innovation.

V. ANALYTICAL TECHNIQUES FOR S&T PLANNING AND MANAGEMENT

John Meyer

INTRODUCTION

This chapter reviews analytical techniques and methods that can be used to support S&T planning and management within MDA/AS and identifies those techniques that should be given the highest priority for application. This is a broad survey of techniques used within government and industry to support activities such as research strategy development, generation of research concepts, project definition and assessment, and similar research planning and management activities. What follows is summary of the tools available, a discussion of the most suitable tools for each area of application, and a recommended short list of tools and techniques MDA/AS should consider for near-term implementation. The treatment is broad but relatively shallow. Thus, the results can be considered an initial "directory" of tools and techniques that can serve as a source for selecting specific methods that can be embedded in MDA/AS's overarching approach to S&T planning and management, with particular emphasis on those tools that can add to the longer term aspects of the innovation process.

The planning and management of MDA's S&T program involves a wide range of functions, including activities such as:

- Environmental scanning to maintain an awareness of changing needs and emerging technologies.
- Development of research strategies to guide program planners and managers.
- Determination of focus areas, be they key technical challenges, specific promising technologies, or important solution approaches.
- Identification and development of project concepts that may be considered for funding.
- Selection of specific research projects to be pursued.
- Management of on-going projects to bring them to successful completion or termination.

- Transition of research results to other MDA elements or other users.
- Provision of infrastructure capabilities needed to support the research program.

Several examples of these types of functions can be found in the MDA Phase II pilot study.[1] As part of this pilot effort, the project team defined processes for identifying alternative missile defense concepts, developed scoring models for ranking the concepts, and established methods for mapping systems concept technology needs to core technologies. Similarly, a method of linking MDA to external technology sources has been identified as a needed capability during IDA's interaction with the sponsor.

A large and rapidly growing group of tools and techniques has emerged during the past few decades to support the above-mentioned S&T planning and management functions within both industry and government. These methods range from high-level management concepts, like the use of stage-gate project-management frameworks to oversee a collection of research projects, to relatively narrow analytical tools for performing specific functions, such as applying qualitative or quantitative scoring models to evaluate and select individual projects for funding. Particularly important are advancements in tools such as modeling and simulation that have been made in recent years to support S&T planning and management.

IMPLEMENTATION ENVIRONMENT AND OPTIONS

Although many tools and techniques exist to support S&T management functions, a significant number are not applicable to MDA's situation or would require considerable modification from their original form to satisfy MDA's needs. For example, many commercial tools and techniques focus heavily on financial parameters, such as return on investment, or on market share data as a basis for analysis and decision-making. Such techniques would have limited utility to MDA or would need to be reworked to incorporate measures of effectiveness relevant to MDA.

Beyond this issue of user focus (i.e., defense research applications versus commercial product development), selection of MDA research planning and management tools and techniques also needs to take into consideration a number of other implementation issues. The tools and techniques should:

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1 Richard Van Atta, et al., "Results of a Technology Assessment Pilot Project for the Missile Defense Agency," forthcoming.

- Be consistent with DoD S&T policies, planning procedures, strategies, and recent changes in this area, such as the newly revised DoD 5000-series regulations and instructions.
- Be compatible with current and anticipated MDA research planning processes, and appropriately interface with budgetary processes and the generation of such documents as the TOG (Technical Objectives and Goals) document, the Enhancement Plan, and the BMDS Integrated Program Plan.
- Comply with established DoD norms regarding interfacing with the private sector from an information sharing, planning, and contracting perspective.
- Take into consideration staffing procedures and possible constraints in this area or provide suitable alternative solutions to bring the appropriate human resources to bear on the problem.
- Recognize the different stakeholders that will participate in the research planning and management process within MDA, DoD, other government agencies, industry, and academia, as well as possibly foreign collaborators.

A number of the tools described in this report have already been or are being used to some extent by MDA/AS. No attempt was made to determine how the techniques presented herein would be integrated with MDA/AS's existing methods. It is assumed that implementation details (e.g., priorities, timing, and resources) will be determined in the future. Any implementations of the techniques contained in this report would likely to be incorporated in and consistent with existing MDA/AS planning and management frameworks.[2] Implementation of new planning and management tools must also be pursued in a manner consistent with other priorities and resource limitations within MDA. Furthermore, it is logical to assume that some of these tools and techniques should be implemented in a sequential rather than a parallel manner and that it may take several years to achieve implementation of the entire set of capabilities envisioned. Implementing the new S&T planning and management tools could be accomplished through a combination of hiring additional MDA staff or by contracting to outside sources, depending upon such factors as timing, resource levels, staffing ceilings, suitability for outsourcing, and similar factors. It may also be desirable to contract for some functions in the early stages of implementation and then migrate to in-house operations at a later date. Thus, an overall implementation strategy and multiyear implementation plan will most likely be required.

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2 Existing MDA/AS planning and management frameworks are described in several documents, including (1) "The Way We Do Business – The BMDA Integrated Program Plan," MDA, 11 June 2003 (Draft); (2) Block Enhancement Plan; (3) Technology Enhancement Plan; (4) System Evolution Plan; and similar publications.

DESCRIPTION OF SOLUTION ELEMENTS

A variety of tools and techniques have been identified to support S&T planning and management functions, and many of these tools will support more than one function. More than 40 different analytical tools and management techniques have been identified.[3] Many of the most relevant tools are briefly discussed in this section; all of the identified tools are summarized in the appendixes.

For discussion purposes, the tools have been organized into five categories:

- Management tools.
- Planning tools.
- Assessment tools.
- Survey tools.
- Forecasting tools.
- Other tools and techniques.

In addition to identifying individual tools and techniques during the task, each was characterized in terms of its purpose and benefits and overall approach. These methods are summarized by category in the appendixes.

The reader should note, however, that the tools may not fall cleanly in one category. For example, the technique of Delphi forecasting, in which experts are polled concerning the likelihood and timing of future events, can be viewed as a survey method, an assessment tool, and a forecasting process. Thus, the category a specific tool or technique has been placed in is somewhat arbitrary. More in-depth discussions of how three of these techniques (stage-gate processes, scoring models, and modeling and simulation) can be tailored to MDA/AS's needs are presented in later sections of the report.

Management Tools

A number of management concepts have been developed to support the planning and execution of research programs. A number of these methods were uncovered during the Phase I study, and several of these (i.e., the use of key technology steering groups,

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3 The definition of an "analytical" tool or technique is somewhat arbitrary and subjective. An attempt was made to include those methods that are recognized as supporting S&T planning and management functions. If there was some question about whether a method is "analytical," we erred on the side of inclusion. Thus, all techniques presented in this report may not be viewed as being analytical by all readers.

innovation hubs, and networking and outreach techniques) have been explored in more detail in chapters of this report.

Management concepts to support research planning and execution cover a wide range of techniques, from broad frameworks to narrowly defined approaches focusing on specific aspects of research management. Some of the more relevant concepts for MDA's needs include the following:

> *Early stage-gate processes*—A stage-gate process is a structured framework for managing R&D projects, where the stages represent the phases or steps the project must progress through, and the gates refer to review points or intermediate milestones where the progress and future direction of the project are reviewed against a set of previously defined criteria. Stage-gate processes are widely used in industry to support commercial product development, and several proprietary versions of the technique are available to speed implementation. Stage-gate systems are typically used to (1) guide decisions on which project to fund; (2) align projects with R&D and organizational objectives; (3) provide guidance on project definition, including scope, desired outputs, integration, and transition of results; and (4) review projects to ensure progress, programmatic fit, and priority. Perhaps one of the best examples of a stage-gate technique is the DoD weapon system development process, which has highly structured milestones and intermediate RTD&E activities.
>
> Some users have observed that a stage-gate process is best suited for managing well-defined product development efforts and that it does not handle the early "fuzzy front end" of R&D very well. However, a number of organizations have successfully addressed this criticism by modifying the technique to encourage innovation in the early stage of the process while still maintaining a structured management approach. One variation of this approach is referred to as the technology stage-gate method, which, for example, has been implemented by DuPont as its APEX process.
>
> A similar but customized process to define and manage early research and technology projects would appear to be an essential need for MDA. Such a process would be designed to feed new component technologies and systems concepts into MDA's overall research, development, test, and evaluation (RDT&E) pipeline and provide the necessary internal and external linkages and

integration to ensure success. (A stage-gate process for MDA/AS is discussed in more detail later in this chapter.)

Benchmarking and performance metrics—The use of benchmarks and performance metrics to evaluate research management is becoming increasingly common, particularly in industry. A number of leading research organizations have made the use of benchmarking and performance metrics an integral part of their management approach to ensure they are doing everything possible to increase performance and satisfy the needs of their parent organization. Sometimes benchmarking is also used to compare the performance or capabilities of different technologies, products, or research facilities to determine which represent state-of-the-art, or world class, levels of accomplishment.

Portfolio management—This is a relatively straightforward but important management tool that helps ensure balance among various types of projects within a research program. Such an approach would typically establish minimum funding levels for categories of projects. These categories might represent technical risk (high versus low risk), application time frame (long-range versus near-term), type of innovation (radical versus conventional), targeted end-use applications (boost-phase intercept versus terminal-phase intercept), technologies (sensors versus integrated battle management), or type of project (applied versus fundamental research). Using this approach, a minimum level of aggregate funding, for example, would be specified for key technologies, radical innovation projects, or projects supporting existing program elements, thereby ensuring that advances are pursued in each of these areas.

Portfolio management is also used for periodically evaluating individual research projects within a category to ensure that each project is handled appropriately, whether it be accelerated, scaled back, or terminated based on the latest information, and is strategically aligned with current organizational priorities.

Strategic technology alliances—Formal collaboration mechanisms are being increasingly used by research organizations to extend their technology coverage and improve their resource effectiveness. In the case of MDA, this could prove to be an effective management strategy by leveraging ongoing research being pursued by other DoD, Federal, and nongovernment programs.

Cross-functional teams—Cross-functional teaming arrangements are routinely used today to define and manage research projects, to bring broad expertise and

perspectives to bear during early definitional stages, and to speed and smooth the transition of results. How cross-functional teams are planned, formed, and managed can have a major affect on the success of the research project. Cross-functional teams are particularly relevant for research in technologies that will be used in complex systems, such as those developed by MDA.

The above represents a few of the management tools and techniques that can be used by MDA/AS to plan and manage its S&T program. Additional details on these tools are presented in Appendix C, Table C-1, along with summaries of several other methods.

Planning Tools

Research planning methods are generally used to produce fundamental decisions and actions that shape and guide what a research organization is and does. Such techniques are typically used to (1) turn mission and vision statements into actions, (2) bring structure and measurement to research planning, (3) develop strategic priorities, (4) communicate research priorities and guide decision-making, and (5) assess future scenarios and select strategies to deal with those outcomes.

Although strategic planning is practiced in most large research organizations, it is not universally loved and respected. Based on at least several decades of practical experience, a number of observers question whether strategic planning is worth the effort:

> A good deal of corporate planning I have observed is like a ritual rain dance; it has no effect on the weather that follows, but those who engage in it think it does. Moreover, much of the advice and instruction related to corporate planning is directed at improving the dancing, not the weather.[4]

However, others feel equally as strongly that strategic planning is a desirable and essential tool that needs to be used by all organizations, including research groups. This is based on the belief that the insight and consensus gained through proper strategic planning far outweigh the adverse effects of inaccurate plans. If nothing else, strategic planning forces an organization to address risks and internal and external trends, thus enabling a faster, more appropriate response to changes.

Regardless of where one stands on this philosophical debate, the following points are clear with respect to strategic planning for research programs:

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4 Russell Ackoff, *Creating the Corporate Future*, John Wiley & Sons, 1981.

- Strategic planning is not the same as forecasting or predicting the future, and should not be viewed as guaranteeing success, only increasing its likelihood.
- Strategic planning, particularly in support of research programs, needs to carefully balance a top-down analysis of trends and issues with the bottom-up generation of new ideas in a way that does not stifle major innovations.
- Research-related strategic planning should explicitly take into consideration the possibility of radical changes in technologies, threats, product features, and other underlying factors—be they internally or externally generated—that could dramatically alter demand for the parent organization's products.[5]

Since MDA already has a strategic planning system (as outlined in the BMDS Integrated Program Plan), the issue is not whether such planning should be undertaken. Rather, it is a question of how planning for research programs should be performed and interfaced with MDA's overall strategic plan. A few of the planning techniques that could prove useful in this regard are briefly mentioned below.

SWOT (strengths, weaknesses, opportunities, threats) analysis—This is a widelyused technique for examining how an organization can perform relative to its mission, capabilities, and environment. The SWOT technique provides an overall view of the organization and the factors that affect its performance, establishes a baseline for creating strategies that address key issues, and points to critical issues that must be addressed if the organization is to succeed. This tool is often used as part of a traditional strategic-planning system.

Balanced scorecard—This is a planning and performance measuring technique that is often used by commercial organizations. It traditionally focuses on balancing four performance dimensions: (1) customer perceptions of how the organization is performing; (2) internal perceptions of how the organization is doing and what it must excel at; (3) innovation and learning performance; and (4) financial performance. In each dimension, appropriate goals and performance metrics are established and tracked. What makes this technique attractive to users is the overall balance it brings to planning and execution, which if properly structured keeps the organization focused on those activities that truly affect its success. Obviously, to be of use to MDA/AS, the performance dimensions and resulting goals and metrics would need to be customized to MDA/AS's specific

5 Motorola refers to this as being sensitive to the "gotchas" that represent research leading to innovative products or new product features that can quickly change market dynamics. Some of these technologies can be developed by competitors, while others may be produced internally by Motorola.

research circumstances, strategies, and priorities, rather than addressing overall MDA issues.

Technology road mapping—Road-mapping techniques cover a wide range of planning methods that have been used with varying degrees of success to define long-term research programs. What most of these road-mapping techniques have in common is the use of some type of graphical representation of technology evolution or technology plans mapped against time. Such a map is used to guide research and new technology development or for selecting technologies to be used in long-term new product development.

However, most road-mapping exercises involve much more than just the generation of a graphical map. They often start with a long-term vision for a technology or product. This vision is compared with the current state of the art to identify technology gaps or voids that need to be addressed and technical barriers that need to be overcome to achieve the vision. The research needed to fill these gaps and overcome the barriers is then identified and laid out in a time-based program to produce the road map.

Although road mapping can be a useful planning tool, it must be used cautiously to avoid several common pitfalls. Unfortunately, road mapping has gained a poor reputation in some instances because it became an end rather than a means for S&T planning and, in some cases, stifled innovation due to political factors or too restrictive a view of what was technically possible. Thus, road-mapping efforts must be carefully planned and managed to ensure they do not distort the S&T program in undesirable ways.

One of the best examples of an effective road mapping technique is the GOTChA (Goals, Objectives, Technical Challenges, Approaches) methodology that has been used successfully for the IHPTET (Integrated High Performance Turbine Engine Technology) program in the 1990s and that is now being applied to the Future Combat Systems and VAATE (Versatile Affordable Advanced Turbine Engine) programs. GOTChA is a planning technique that maps systems-level performance and technology goals to R&D activities needed to achieve the goals. The technique provides a framework for determining goal-directed S&T program requirements. GOTChA helps ensure that S&T funds are spent in a focused and productive manner and provides a tool for monitoring progress of individual

technology efforts. In many respects, GOTChA is a quantitative technology road-mapping technique.

An example of a high-level GOTChA chart for the Army's Future Combat System is shown in Figure V-1. This example illustrates how high-level systems goals are broken down into more focused objectives, technical challenges, and solution approaches.

These and other planning tools and techniques are summarized in Appendix C, Table C-1.

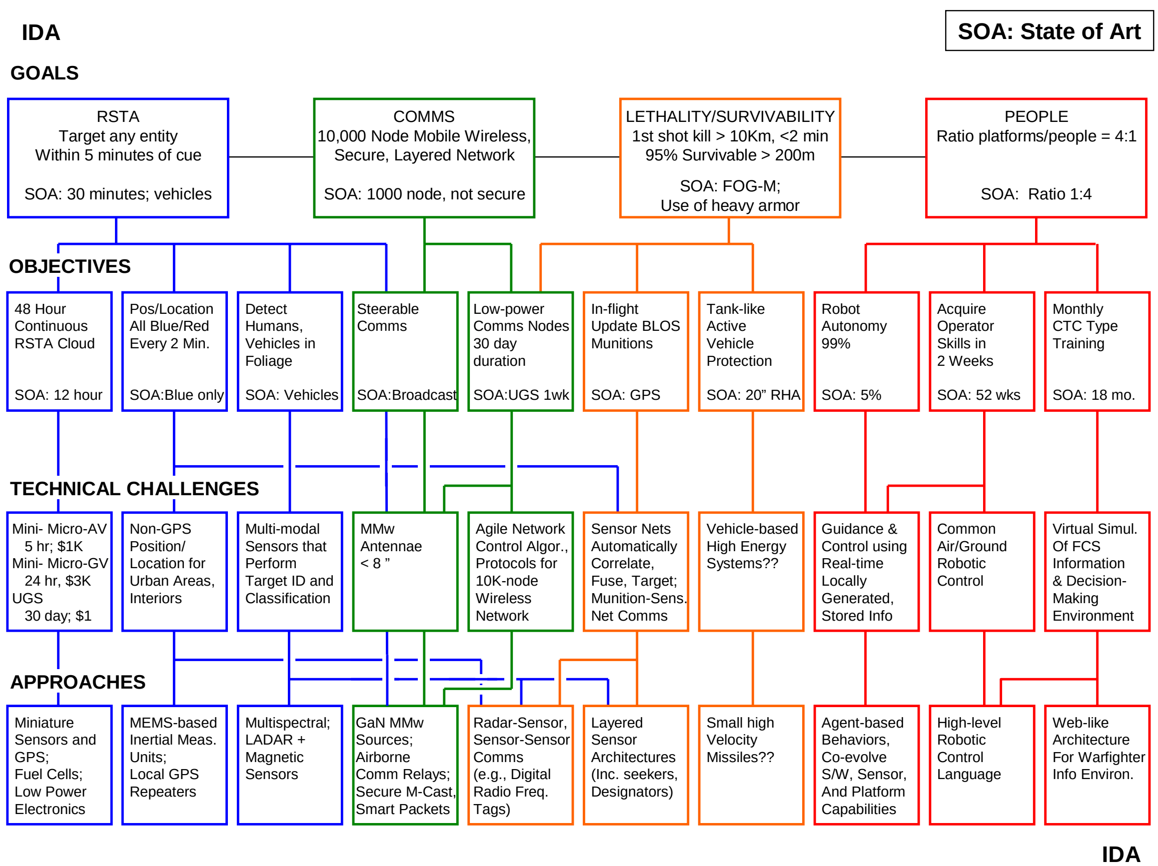

Figure V-1. Example GOTChA Chart for the Army's Future Combat System (Source: Donald Dix, "The GOTChA Methodology," IDA, 15 May 2002)

Assessment Tools

Assessment tools are used for a variety of reasons in planning and managing research programs. For example, assessment models can be used to evaluate individual

projects so that the most suitable or highest priority can be selected for funding. Other types of assessment models may be used to evaluate the impact of new technologies on product performance or to identify areas (e.g., subsystems or components) having the greatest potential for technical improvement. Still other types of assessment techniques can be used to decompose problems or challenges in a way that facilitates the identification of appropriate solutions. And still other types of assessment models, such as the DoD Technology Readiness Levels, are used to determine the maturity of technologies and their readiness to move down the product development pipeline.

A large number of assessment tools have been developed to support research activities. A few of the more relevant to MDA/AS's needs include the following:

> *Simulation models*—Simulation models are widely used to assess the impact of new technologies on the performance of products without the need to construct and test physical prototypes, which are particularly costly in MDA's case. Such models have been particularly important in support of defense and aerospace product developments. One example highlighted during the Phase I project was the role the Visionics quantitative performance models played in the development of night vision technology. In this case, the Visionics models provided objective criteria for assessing system and component performance. The use of these models for R&D planning and assessing options before investment proved to be an effective means of allocating resources.
>
> MDA is already using a variety of simulation models to assess the overall performance of missile defense systems and subsystems. However, additional models to support analysis of key technologies, important technical challenges, and emerging solutions will undoubtedly be needed in the future.
>
> Simulation and modeling as a tool for use by MDA/AS is discussed in Chapter VI of this report.
>
> *Project and technology assessment tools*—These tools are needed to enable research managers to objectively evaluate alternative projects and technologies in terms of their potential contribution to future MDA systems. These assessment models can range from relatively straightforward checklists to ensure that major issues have been addressed, to elaborate multivariable scoring models to rank alternatives in a more quantitative manner.
>
> *Problem assessment techniques*—A large number of assessment techniques exist for analyzing various problems or technical challenges. These vary widely in

complexity and include techniques such as affinity diagrams, cause-and-effect (fishbone) diagrams, conjoint (trade-off) analysis, decision trees, gap analysis, influence diagrams, morphological matrices, prioritization matrices, radar/spider charts, scenario analysis, sensitivity analysis, and strategy space models.

Each of the above techniques and others are summarized in Appendix C, Table C-3. Collectively, these represent a broad spectrum of tools that MDA research managers can draw upon to assess research needs and options.

Survey Tools

Few research organizations could operate without inputs from outside the organization. Information from customers and end users, other elements within the organization, and outside experts are used to identify research needs, develop new solution ideas, and evaluate alternative project concepts. Some of the survey tools available to support the collection and analysis of this type of information include the following:

Structured brainstorming—Brainstorming is a method of creative problem-solving frequently used in research and product concept generation. There are many variations of the brainstorming format. The basis of all these methods is to use a group of appropriately selected people to creatively generate a list of ideas related to a particular challenge or objective. Some brainstorming processes are highly structured to increase the chances of yielding radical innovative solutions. Keys to brainstorming success include (1) selecting the right participants, (2) keeping the process focused on actionable objectives, and (3) facilitating the interactions in a manner that minimizes negative dynamics among the participants that would limit creativity. In addition to the generation of innovative new solutions, other brainstorming benefits include (1) improved teamwork and commitment to action, (2) reduced fear of competition and overcoming project obstacles, (3) creating a high volume and wide variety of actionable ideas, and (4) increased appreciation for nontraditional thinking.

Brainstorming was one of the techniques used by the IDA Phase II pilot task team for initial identification of innovative missile defense concepts, which were later detailed, refined, and analyzed to identify important S&T challenges.

Brainstorming techniques are often employed in conjunction with the types of assessment tools discussed in the previous section; here, the brainstorming

sessions are used to generate many ideas and the assessment tools are used to evaluate, rank, and refine them.

Nominal group techniques—These represent a variety of methods for generating ideas about a particular subject and building team consensus about priorities. Although similar to brainstorming, the emphasis on nominal group techniques is to ensure equal team member participation in identifying and ranking of issues and solutions and build team commitment to the outcome of the process. Whereas brainstorming concentrates on generating solutions, nominal group techniques focus on achieving consensus results.

Internet-based surveys—The Internet is increasingly being used as a tool for collecting opinions. These collections range from wide surveys of inputs from any source to more structured collections of expert opinion. For example, some government agencies now use the Internet for collecting inputs from evaluation panels who are reviewing research proposals. Such Internet-based tools will become increasingly important in the future, particularly for real-time, collaborative data collection and analysis.

These and similar survey techniques are summarized in Appendix C, Table C-4.

Forecasting Techniques

Techniques for forecasting technological trends often play an important part in research planning, especially in situations where incremental or leap-ahead technical advancements can have a major impact on product performance. However, forecasting technology trends under these conditions is especially difficult.

Some individuals like to draw a distinction between forecasting and foreseeing future developments. However, both are an attempt to predict what will happen in an uncertain world. Perhaps a more useful distinction is between extrapolative techniques, which are based on projections derived from past data and trends, and normative forecasting techniques, which rely on a more subjective analysis of possible future events and technology developments, where there is little hard data available on which to base decisions.[6] Thus, extrapolative forecasting techniques tend to be quantitative and build on actual data or similar historical models, whereas normative methods are typically

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6 Brian Twiss, *Forecasting for Technologists and Engineers: A Practical Guide for Better Decisions* (London: Peter Perigrinus, 1992).

speculative and qualitative and are based on expert opinion and insight on many technical and nontechnical factors. Although both approaches are important in early stages of R&D, normative forecasting methods are particularly useful in predicting the timing and impact of technical developments that have not occurred yet. Normative techniques are also used to determine the feasibility of achieving a given technical or systems capability within a required time frame and cost and thus are useful for assessment as well.

A large number of technology forecasting techniques have been developed and applied for research planning purposes, with widely varying degrees of success. These include methods such as:

- *Trend extrapolation*—Projecting future directions based on trends derived from historical data.
- *Pattern matching techniques*—These include the analysis of patents and scientific papers in particular technical areas.
- *The use of forecasting "laws" and models*—These include the use of Moore's law to predict the exponential growth in the number of transistors per integrated circuit.
- *Scenario analysis*—Scenario analysis results in forecasts that explicitly recognize that future events are not deterministic by examining the impact of several feasible alternatives. This technique also helps decision-makers become more sensitive to signals of impending change.
- *Expert opinion*—Expert opinion, especially based on consensus-building approaches, is a widely used approach to technical forecasting. A good example is the Delphi method, a technique that uses iterative rounds of polling across a group of experts to arrive at a forecast of the most probable outcome for some future state.

These methods and others are summarized in Appendix C.

Other Tools and Techniques

In addition to the methods mentioned above, other types of tools and techniques can be used to support research activities:

> *Groupware for project planning and management*—Software to enable collaboration among research managers and other participants in defining and managing research projects is becoming increasingly popular. Such systems help to automate the following functions: (1) capturing ideas, (2) transcribing ideas into electronic format, (3) organizing data and relationships, (4) creating action plans, and (5) distributing information electronically. A system of this

type to support MDA/AS's requirements would most likely need to be custom designed.

Environmental scanning methods—Keeping abreast of technological and other developments that would affect a research program is a major challenge for research organizations. Although environmental scanning is often viewed as an integral part of the strategic planning process, relatively few tools are available to perform this function. To overcome this problem, some organizations have created dedicated capabilities to perform the scanning function. These include specific staff responsible for tracking and reporting developments and trends, the use of internal newsletters to communicate important information, subscription to various technical intelligence services, and commissioning periodic scanning studies, among others.

Knowledge management—This tool has not lived up to its much-publicized potential, thus resulting in considerable skepticism among research managers. However, the basic premise of knowledge management—namely, the need for an organization to more effectively utilize its knowledge—is still fundamentally sound. To this end, research organizations are developing tools, such as online information repositories, to catalog and make available relevant information to research managers and other users within the organization.

Mind mapping—Mind mapping is one of several methods of brainstorming, planning, meeting facilitation, and implementing action plans that rely on conceptual mapping techniques to capture and communicate concepts and increase team collaboration and productivity. Usually computer-based, mind maps automate the functions of (1) capturing ideas, (2) transcribing ideas into electronic format, (3) organizing data and relationships, (4) creating action plans, and (5) distributing information electronically.

Staffing experiments—There has been a growing awareness in recent years that there may be a correlation between an individual's personality type and success as a technological innovator. Thus, some research organizations are beginning to use personality type indicators (e.g., the Myers-Briggs Type Indicator) as one criterion when selecting research managers. This approach, if it continues to prove correct, raises some interesting possibilities in helping

managers to ensure that individuals are assigned to the right types of jobs to optimize research effectiveness.

These and other tools are summarized in Appendix C.

As mentioned earlier, many of the tools and techniques apply to more than one S&T planning and management function, as illustrated in Table V-1.

Table V-1. Examples of Tools and S&T Planning and Management Functions

Analytic Tools	S&T Planning and Management Functions							
	Scan environment	Develop strategies	Determine focus areas	Identify concepts	Select projects	Manage projects	Transition results	Infrastructure
Management tools								
-- Stage-gate process					X	X	X	X
-- Benchmarking					X	X		X
-- Portfolio management		X	X	X	X	X		
Planning tools								
-- SWOT analysis	X	X	X					
-- Score cards	X	X	X					
-- Road maps	X	X	X	X	X			
Assessment tools								
-- Modeling and simulation		X	X	X	X			
-- Project scoring models				X	X	X		
-- Trade-off analysis		X	X	X	X			
Forecasting Tools								
-- Delphi forecasts	X	X	X	X	X			
-- Trend analysis	X	X	X	X	X			
-- Scenario analysis	X	X	X	X	X			
Survey tools								
-- Brainstorming	X	X	X	X				
-- Nominal group method	X	X	X	X				
-- Internet surveys	X	X	X	X	X	X	X	
Other tools								
-- Mind maps	X	X	X	X	X	X	X	X
-- Management groupware		X	X	X	X	X	X	X
-- Knowledge management		X	X	X	X	X	X	X

To illustrate how these techniques could be applied to MDA's S&T planning and management, three examples have been selected for further elaboration: early stage-gate processes, scoring models for project evaluation and selection, and simulation and modeling. Stage-gate and scoring models are described in the remainder of this chapter. The next chapter delves into simulation and modeling.

MDA/AS STAGE-GATE PROCESS

As discussed previously, a stage-gate process is a structured framework for managing R&D projects, where the stages represent the phases or steps the project must

progress through, and the gates refer to review points or intermediate milestones where the progress and future direction of the project are reviewed against a set of previously defined criteria. Such processes are used by the majority of R&D organizations to (1) guide decisions on which project to fund; (2) align projects with R&D strategies and organizational objectives; (3) provide guidance on project definition, including scope, desired outputs, integration, and transition of results; and (4) review projects to ensure progress, programmatic fit, and priority.[7]

A stage-gate process of this type can be used by MDA/AS to plan and manage early-stage S&T projects. Such a process would begin with idea generation and end at the point when the project is either transitioned to another MDA program element for further development or is terminated. The process would be designed to feed new component technologies and systems concepts into MDA's overall RDT&E pipeline and provide the necessary internal and external linkages and integration to ensure success.

Some users have observed that a traditional stage-gate process is best suited for managing well-defined product development efforts and that it does not handle the early "fuzzy front end" of R&D very well. However, this criticism has been successfully addressed by a number of organizations that have modified the process to encourage the necessary flexibility in the early stages and still maintain a structured management approach. One variation of this approach is sometimes referred to as the "technology stage-gate method," which has been implemented by several firms, including DuPont as its APEX process, as described in the Phase I report.

With these comments in mind, an early stage-gate process along the lines discussed below is recommended for MDA/AS. This process, tentatively referred to as the "MDA Innovation Process," or MIP, is illustrated in Figure V-2. This is an initial framing of the process, and will need to be refined in detail in cooperation with MDA/AS personnel.

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7 Abbie Griffin, "Product Development Management Association Research on New Product Development Practices: Updating Trends and Benchmarking Best Practices," *Journal of Product Innovation Management*, Vol 14, 1997, pp. 429–458.

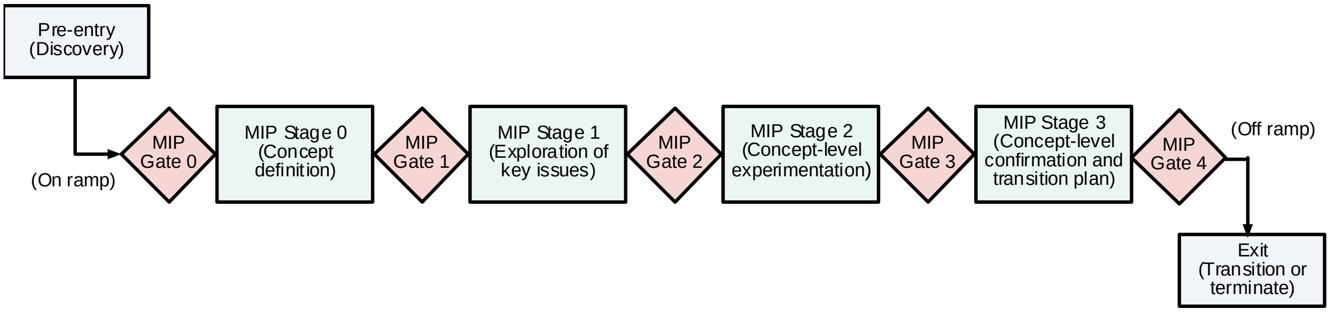

Figure V-2. MDA Innovation Process

The proposed MIP is a four-stage process that begins with concept definition and ends with either the transition of the concept to another MDA organization for further development, or termination, which can take place at any of the review gates.

Before describing the MIP in more detail, the reader should note a few important points. First, although the MIP may look like a uniform process, in reality it is very flexible. It is applied according of the needs of the specific project being reviewed and the type of concept being developed. In MDA/AS's case, the majority of projects will be one of the following types:

- *Platform (or flagship) projects*—These are projects that would radically change the way missile defense is performed.
- *Leap-ahead projects*—These are projects that represent a major advancement in an underlying technology, component, or subsystem.
- *Strategic technology projects*—These are projects that represent emerging technologies that have the potential to dramatically change components, subsystems or systems but where the application has not yet been well defined.

Because of the significant differences between these types of projects, the tasks that would be undertaken in each MIP stage could vary considerably. The issues that would be examined during each MIP gate would similarly differ depending on the type of project being reviewed. Thus, the stages and gates for any particular projects would be custom tailored to the needs of the concept. And it is likely that MDA/AS will undertake some projects that would not be managed with the MIP. These could range from broad investigations and planning studies to fast-track activities and more near-term problem solving.

The second point is that the process is dynamic. Since the stage-gate process serves as the wellspring of advanced concepts for MDA/AS, it must accomplish the following objectives:

- *Refining the concept*—Especially in the early phases of the process, refining (or tuning) the concept is not an easy matter. For example, going from the concept of using nanotechnology to a specific, implementable application would require considerable effort to sort out options to ensure the right target is selected.
- *Determining if the concept is actually possible*—In the broadest sense, determining whether a concept has any chance of really working is not straightforward. A good example here is the case of inertial guidance technology. Early on, many experts argued that it simply was not possible; this hurdle had to be overcome to proceed with development of the concept.
- *Determining if the concept is practical*—Many concepts may be technically feasible but totally impractical. Sometimes the introduction of a new technology causes other unforeseen difficulties that need to be addressed. Again, inertial guidance is a good example. It took many years to achieve the 100-fold or more improvements in component technology needed to achieve practical performance goals.
- *Determining if the concept is desirable*—An innovation may be possible and practical but still not desirable for a variety of economic, political, and social reasons. Similarly, an innovation may languish because it is an unwanted "orphan." If such cases, the challenge would be to implement a strategy that will convert an orphan into a prize.
- *Positioning the technology for the next stage of development or insertion*—The technology stage-gate process feeds into a downstream mechanism for further development. Consequently, the process must lay the groundwork for this transition to make it as smooth as possible. This involves engaging the necessary stakeholders and generating the information required to facilitate the transition. It also implies bringing the technology to a suitable readiness level for transition.

Although these objectives may appear linear (or sequential), they are, in fact, ongoing and take place in parallel. Depending on where the concept is in the stage-gate pipeline, however, each objective has a different level of emphasis, as illustrated in Figure V-3. For example, the issue of refining the concept to be sure the right idea is being pursued is an ongoing challenge. It is especially important in the early stages, but the concept is still fair game for modification until the innovation emerges from the pipeline.

Stages / Objectives	Pre-entry (Discovery)	MIP Stage 0 (Concept definition)	MIP Stage 1 (Exploration of key issues)	MIP Stage 2 (Concept-level experimentation)	MIP Stage 3 (Concept-level confirmation and transition plan)
Refine concept	●●●	●●●	◑◑	○	○
Determine possibility	○	◑◑	●●●	◑◑	○
Determine practicality	○	○	◑◑	●●●	●●●
Establish desirability	○	○	○	◑◑	●●●
Position for transition	○	○	○	◑◑	●●●

●●● = Primary focus　　◑◑ = Major issue　　○ = Minor issue

Figure V-3. MDA/AS Innovation Process Stages and Objectives

Even the idea of concept definition is not linear. As shown in figure V-3, it may require many iterations and morphing to produce a concept that is suitable for entry into the stage-gate pipeline. This initial phase is sometimes referred to as the “fuzzy front end” of stage-gate processes. Thus, Figures V-3 and V-4 show that the proposed innovation process is far from linear, though the pipeline itself is a set of sequential phases.

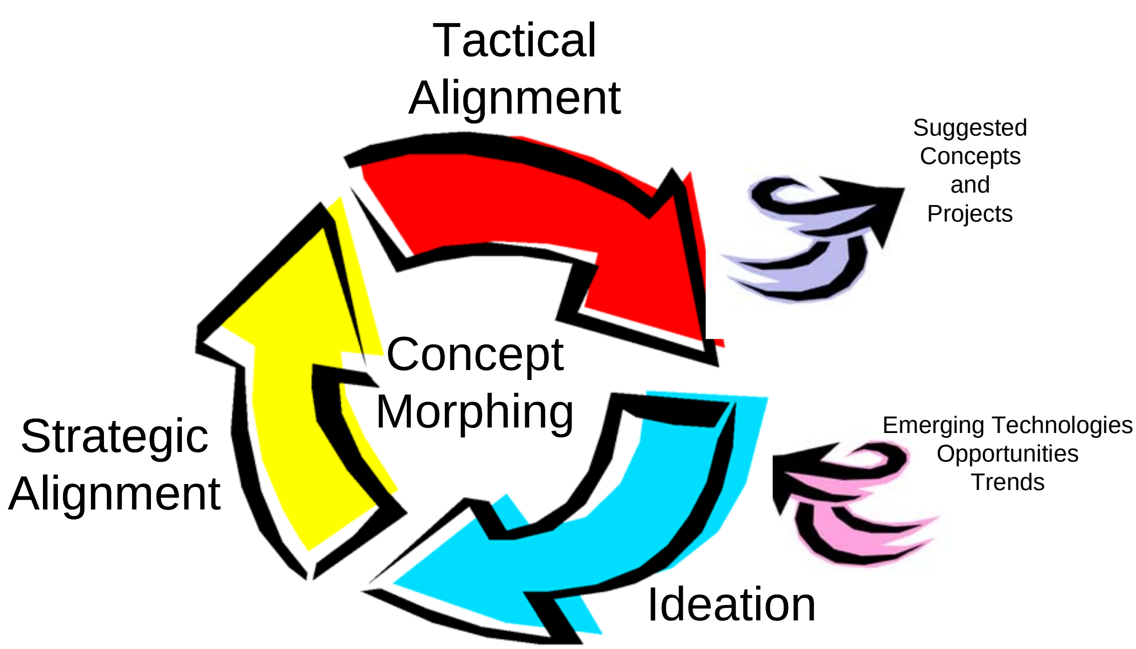

Figure V-4. “Fuzzy Front End” of Stage-Gate Process

The message here is that the innovation process, especially in its early stages, is inherently difficult to predict because of the dynamic nature of the issues and risks, and each project must be handled on a case-by-case basis as it evolves. And as mentioned earlier, an ability to cope with and even thrive in this type of fluid, vibrant, entrepreneurial environment must be reflected in the staff assigned to manage and participate in the process.

The third point the reader should note is that there will be significant effort required of MDA/AS both before and after the MIP. For example, before entry (the "discovery" phase), a number of important activities would be performed, including:

- Information gathering.
- Needs and technology analyses.
- Opportunity identification and idea generation. (These ideas and project suggestions may come from many sources, including Broad Area Announcements, Small Business Innovation Research programs, and other solicitations; unsolicited proposals and external project suggestions; hunters and gatherers and other internal MDA sources; Strategic Technology Steering Committees; and various workshops and studies.)
- Strategic and tactical alignment of ideas to conform to MDA's needs and S&T strategy.
- Assignment of an appropriate project leader.
- Initial definition of the concept and MIP Stage 0 project.

Therefore, even before entering the MIP, considerable work would have been accomplished, and information to be reviewed at Gate 0 (the on ramp to the MIP) would, at minimum, include

- Initial concept and project definition:
  - Background and description of the technology.
  - Potential MDA applications and benefits.
  - Stage 0 plan and resource requirements.
- Identification of the designated project leader.

Similarly, MDA/AS's work would not stop at the end of the MIP. Depending on the needs of the specific concept, post-MIP activities include, at minimum, transition support to the receiving MDA organizational element and follow-up data collection to track implementation issues and impact. In some cases, post-MIP activities may also include transfer of personnel to assist in the transition.

The last important point the reader should note is that the MIP represents a funnel-shaped pipeline in which the number and dollar of value of projects in each stage varies inversely. Thus, a relatively large number of projects may be underway in MIP Stage 0, but at each succeeding gate, many of these projects are weeded out, resulting in a small number of concepts that are successfully transitioned to other MDA organizational elements. Similarly, as a concept progress down the pipeline, the cost of the next next-phase project increases, sometimes dramatically. This funneling affect is illustrated in Table V-2. For even the best managed R&D organizations, the fallout rate from concept definition to full implementation is about six or seven to one.[8] Thus, under the best of circumstances, it takes starting at least six concepts in the funnel to yield one successful implementation. Moreover, the managing organization must be disciplined and focused to move forward with those projects that have the highest relevancy to the organization and to terminate or rework those concepts that are of lesser priority.

Table V-2. Relative Number of Projects and Project Values by MDA Innovation Process Stage*

MIP Stage	Number of Projects	Avg. Project Value ($K)	Value by Type ($K)	% of Total Funds
0 – Concept definition	10	500	5,000	5%
1 – Explore key issues	5	5,000	25,000	25%
2 – Concept-level experimentation	2	10,000	20,000	20%
3 – Confirmation and transition plan	1	50,000	50,000	50%
Totals	18	5,600	100,000	100%

* The values used in Table 2 are only for the purpose of illustrating the relationship between project stages and could vary considerably based on actual circumstances.

We discuss each MIP stage in turn.

Stage 0 (Concept definition)—As the name implies, the purpose of Stage 1 is to further define and refine the concept that will be pursued in the MIP. Typical tasks that would be undertaken in this stage include the following:

a. Form a multidisciplinary project team. The size and composition of the team will obviously vary according to the needs of the project, and the team can be expanded as the concept progresses through the MIP.

b. Identify ongoing research, key researchers, and research needs.

c. Study MDA uses, benefits, and important application issues.

8 Ibid.

d. Determine key barriers, research needs, and risks that need addressing.

e. If appropriate, explore the possibility of finding other research collaborators within and outside DoD to leverage S&T resources.

f. Develop a detailed Stage 1 plan, success criteria, and resource requirements.

g. Develop preliminary plans for Stages 2 and 3 and estimate resource needs.

h. Review Stage 0 findings with a Strategic Technology Steering Group, if appropriate

i. Develop a team recommendation regarding "go" or "no-go" for Stage 1.

Stage 1 (Exploration of key issues)—During this phase, the project will focus on resoling the key issues identified during Stage 0. Typical tasks during Stage 1 include the following:

- Expand or modify of the project team, if needed. This may mean including individuals from other MDA organizational elements that either provide specialized expertise or would be affected by downstream transition of the technology.
- Investigate key technical issues regarding concept feasibility. Since MDA does not conduct research internally, this effort would be performed by contractors or other government organizations under the management of the project team. Thus, making contractual arrangements may be a significant activity during this stage.
- Update MDA applications information, associated benefits, and technical and operational issues for the new technology.
- Review findings with appropriate stakeholders, such as other MDA organizational elements.
- Develop a detailed Stage 2 plan, including success criteria and resource requirements.
- Update the preliminary plan for Stage 3 and estimated resource needs.
- Prepare a Stage 1 report.
- Review findings with a Strategic Technology Steering Group, if appropriate.
- Establish a team recommendation regarding "go" or "no-go" for Stage 2.

Stage 2 (Concept-level experimentation)—During this stage, the innovation will be investigated at the concept level to evaluate overall feasibility. This might be similar to constructing and testing a concept-level "breadboard" prototype to determine initial feasibility at this level, as opposed to creating a more refined "brass board" instantiation of the technology. Typical activities that would be undertaken during MIP Stage 2 include the following:

- Further expansion or modification of the project team.

- Investigation of key technical issues regarding concept-level feasibility. Like the previous stage, this effort would be performed by contractors or other government organizations, under the management of the project team. Thus, contracting details may be a significant activity during this stage.
- Updating MDA applications information, associated benefits, and technical and operational issues for the new technology.
- Reviewing findings with appropriate stakeholders.
- Development of an initial transition plan that would address how the technology would be transitioned within MDA at the end of the MIP.
- Updating the Stage 3 plan, success criteria and resource requirements
- Preparation of a Stage 2 report.
- Reviewing findings with a Strategic Technology Steering Group, if appropriate.
- Establishing a team recommendation on “go” or “no-go” for Stage 3.

Stage 3 (Concept-level confirmation and transition planning)—During this stage, the final step in the MIP, the concept-level feasibility for the innovation is confirmed, and all details concerning how the technology will be transitioned to other elements within MDA are resolved. Activities during Stage 3 would include the following:

- Further expansion or modification of the project team, if needed.
- Additional concept-level demonstrations needed to confirm the feasibility of the innovation. As in the previous stage, this effort would be performed by contractors or other government organizations under the management of the project team. Thus, contracting details may be a significant activity during this stage.
- Finalizing MDA applications information, associated benefits, and technical and operational issues for the new technology.
- Reviewing findings with appropriate stakeholders.
- Finalizing the technology transition plan.
- Preparation of a Stage 3 report.
- Reviewing findings with a Strategic Technology Steering Group, if appropriate.
- Establishing a team recommendation on “go” or “no-go” for transition.

At this point, the innovation will have completed its running of the MIP gantlet and would then, with appropriate Gate 4 approval, move into the transition phase and integrate with other MDA programs. As mentioned previously, even though the MIP has been completed for this technology, MDA/AS would still perform some post-MIP activities to support the transition and track the subsequent success (or failure) of the concept.

It should again be emphasized that, although the stages are conceptually the same, the actual work to be performed during each stage may vary considerably for any particular project, depending on the type of innovation, the level of its application (e.g., component, subsystem or system), and the unique circumstances of the technology being developed. One of the keys to using this type of process is the customization of the work activities, project team, and success criteria, for the innovation being pursued. During the early stages, the emphasis is on technical feasibility; in later phases, the issues of specific MDA applications, affordability, overall desirability, and transitioning become increasingly important. Similarly, the MIP funnel focuses larger resources on fewer projects and involves wider ranges of participants and stakeholders as the innovations flow through the process.

One of the key distinctions between a technology stage-gate process, such as MIP, and a traditional stage-gate process is that the development of technologies is fundamentally different than development of products. Product development using a traditional stage-gate method assumes that the underlying technologies are mature and available. Thus, the emphasis in traditional stage-gate processes is on managing schedules and budgets. Technology development, on the other hand, is in inherently unpredictable, especially in the early stages, where capabilities are explored, feasibility is evaluated, breakthroughs occur, and new solution paths are uncovered and pursued. Consequently, technology stage-gate processes must be more flexible and, in the earlier stages, focus on progress toward meeting essential technology performance goals. These differences between traditional and technology stage-gate processes are also reflected in the review gates that are used to determine the future of the project as it flows through the funnel.

The MDA Innovation Process employs five gates:

> **MIP Gate 0 (On ramp)—**This initial gate determines whether an innovation is ready to enter the MIP funnel. The information to be reviewed by the gatekeepers (discussed later) will primarily be contained in an initial concept definition document. As a minimum, this document will address (1) a description of the technology and why it is important, (2) potential MDA applications and benefits, (3) required advancements or challenges that need to be resolved in order to use the technology, and (4) a Stage 0 plan and resource requirements. Depending on the project, other information may also be included in the initial concept definition document.

During the Gate 0 review, the decision-makers will determine the fate of the project primarily based on (1) the potential for significant MDA applications, (2) how well the project fits with MDA S&T strategies and portfolio balance, and (3) the adequacy of the Stage 0 plans. The gatekeepers may decide to approve entry into Stage 0, terminate the project, or send it back to the discovery stage for rework.

MIP Gate 1 (Entry to Stage 1, exploration of key issues)—At this stage in the MIP, the gatekeepers will have a much better definition of the potential of the technology, key issues that need to be explored, and initial resource requirements. The outputs from Stage 0 that feed into Gate 1 include the Stage 0 report; results of any Strategic Technology Steering Group reviews; a detailed Stage 1 plan, success criteria, and resource requirements; initial Stage 2 and 3 plans and resource requirements; and a project team "go" or "no-go" recommendation. They will use this information to decide if the project should move to the next phase where the research truly begins.

Criteria that will be used to make the Gate 1 decision include (1) the potential for significant MDA applications and long-term impact; (2) the fit within MDA's S&T strategies and portfolio balance; (3) adequacy of identification of key issues, challenges, and risks; (4) reasonableness of proposed Stage 1 plan, success criteria, and resources; and (5) downstream Stage 2 and 3 plans and resource implications.

It is at this gate that many of the concepts will be screened out. In the examples given earlier in Table V-2, as many as half or more of the concepts would either be terminated, postponed, or sent back to Stage 0 for rework. It is this weeding out of lower priority projects that many organizations find difficult. However, this screening function is essential to maintaining a viable, responsive, and effective S&T program. This issue is discussed later.

MIP Gate 2 (Entry into Stage 2, initial concept-level investigations)—During this review, the gatekeepers will decide if the key issues affecting the feasibility of the innovation have been adequately addressed and if enough is known about the technology to begin concept-level investigation. The outputs from Stage 1 that feed into Gate 2 include (1) resolution of—or at least significant progress on—the key issues; (2) the Stage 1 report; (3) results of any Strategic Technology Steering Group reviews; (4) a detailed Stage 2 plan,

success criteria, and resource requirements; (5) an updated preliminary Stage 3 plan and resource requirements; and (6) a project team “go” or “no-go” recommendation for entry into Stage 2.

As with the earlier gates, the decision-makers will decide to move the concept to the next stage, terminate it, or continue it in the earlier stage for more investigation. Again, for the MIP to work effectively, only a limited number of high-priority concepts will be allowed to move forward in the pipeline. The criteria that will be used to make this decision include (1) potential for MDA applications and long-term impact; (2) continuing fit with MDA’s S&T strategies and portfolio balance; (3) resolution of key issues, challenges, and risks (Is the technology is really understood and suitable for the proposed applications?); (4) adequacy of the proposed Stage 2 plan, success criteria, and resources; (5) downstream Stage 3 plan and resource implications; and (6) involvement of other MDA elements and DoD organizations.

MIP Gate 3 (Entry into Stage 3, concept-level confirmation and transition plan)—At this gate, the decision-makers will determine if the concept moves to the final, most expensive, and perhaps most critical MIP stage. At this stage it will complete the groundwork for transitioning the concept to other MDA organizational elements and subsequent development and deployment of the technology. Outputs from Stage 2 to be reviewed by the gatekeepers include (1) an initial assessment of the concept-level feasibility of the technology; (2) an initial transition plan for the technology; (3) a Stage 2 report; (4) results of any Strategic Technology Steering Group reviews; (5) a detailed Stage 3 plan, success criteria, and resource requirements; and (6) a project team “go” or “no-go” recommendation regarding moving forward to Stage 3.

As with the previous gate, the criteria that will be used to make this decision include (1) reaffirming the potential for MDA applications and long-term impact; (2) continuing fit with MDA’s S&T strategies and portfolio balance; (3) resolving all key issues, challenges, and risks; (4) determining the adequacy of the proposed Stage 3 plan, success criteria, and resources; (5) determining the adequacy of the initial transition plan; and (6) involving other MDA elements and DoD organizations. The primary focus of the decision-makers will be on whether Stage 3 will resolve all the issues that will enable a successful transition of the concept after it leaves the MIP.

MIP Gate 4 (Off ramp, the final MIP gate)—This gate represents both the final MIP gate and the beginning of another process, one that will eventually lead to development and deployment of the technology by other MDA organizational elements. Thus the gatekeepers in this instance will be not only the MIP decision-makers but also the senior managers that will determine the fate of the technology after it leaves the MIP. Outputs from Stage 3 that will be reviewed during this gate include (1) the final assessment of the concept-level feasibility of the technology, (2) a finalized transition plan for the technology, (3) a Stage 3 report, (4) results of any Strategic Technology Steering Group reviews, and a (5) project team "go" or "no-go" recommendation regarding transition.

The primary criteria that will be used during Gate 4 are (1) reaffirmation of the potential for MDA application and long-term impact; (2) resolution of all key issues, challenges, and risks; and (3) transition readiness.

The MIP gates are fairly straightforward, but their use implies several subtleties that need to be understood.[9] First, because MIP is a technology stage-gate process rather than a traditional stage-gate mechanism, the MIP gates are driven primarily by technology advancements, which are inherently less predictable than traditional stage-gate phases. This means that MIP gates will often be event driven rather than schedule driven, or more likely, driven by both events and schedules. Thus, MIP gates may be held to coincide with achieving a particular successful performance level for a technology. Similarly, MIP gates may be held when a predesignated showstopping event has occurred, such as concluding that a particular technical capability is not feasible. These event-driven milestones for MIP gates would be specified in the plans for a particular stage. In the event that such milestones are not appropriate or achievable, then conventional schedule-driven gate reviews would be held.

Another subtlety concerns the makeup of the gatekeepers. The gatekeepers are the group responsible for conducting the gate reviews and deciding whether a project should move to the next stage. This committee also approves the tasks to be accomplished during that next phase and the resource levels, subject to the normal budgetary procedures for the project. Typically, this committee would be chaired by the head of

9 Greg M. Ajamian, and Peter A. Koen, "Technology Stage-Gate™: A Structured Process for Managing High-Risk New Technology Projects," in the *PDMA Toolbook for New Product Development* (Product Development and Management Association, John Wiley & Sons, 2002) pp. 267–295.

MDA/AS and would have additional members from within MDA/AS and possibly from other MDA organizational elements (e.g., MDA/SE and one or more MDA project elements). In some cases, a project may also be reviewed by other committees. For example, a project relating to a key strategic technology may also be reviewed by the MDA steering committee for that technology.

In the early stages, the gatekeepers would be a limited number of individuals, primarily from within MDA/AS, that would decide the fate of the projects, subject to review by senior MDA management. This is necessary to ensure that innovative concepts are not killed prematurely. As the concept passes through the MIP funnel, however, the group of individuals serving on the gatekeeping committee would be expanded to include other stakeholders within MDA, depending on the specifics of the concept being investigated. Obviously, these details of the makeup of the gate keeping committees will need to be worked out by MDA/AS.

Because stage-gate processes have become widely used in R&D organizations, several best practices have been developed on how gatekeeping should be performed. These gatekeeper rules of engagement include the following:[10]

- Gatekeepers must hold the meeting and be there. Postponed or canceled meetings are not permitted, and those not attending are considered to be voting "yes" for the project.
- Gatekeepers must have received and read the meeting materials and be prepared for the meeting. No last-minute reading is permitted at the meeting. If there are showstoppers, then the meeting facilitator is contacted in advance so that participants are not surprised.
- Gatekeepers cannot request information beyond that specified in the stage deliverables.
- Gatekeepers must make their decisions based on the criteria specified for that gate. Each criterion must be addressed, and a conclusion reached by the group. A scorecard will be filled out by each gatekeeper.
- Decisions must be based on objective facts and criteria, not emotions or hidden agendas. All projects must be treated fairly and consistently, including uniform application of gates.
- A decision must be made at the meeting, and the project team must be informed immediately and face to face.

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10 R.G. Cooper, S.J. Edgett, and E.J. Kleinschmidt, "Optimizing the Stage-Gate Process: What Best Practice Companies are Doing—Part II," *Research-Technology Management*, Vol 45, No 5, 2002.

Sometimes gatekeeper meetings are difficult to complete because of the busy schedules of senior personnel, travel pressures for geographically separated members, and conflicting workload priorities. To overcome these problems, some companies have been experimenting with concepts such as virtual gate meetings where only the project team is physically at the meeting place. The gatekeepers receive the preparatory documents in advance and participate electronically (e.g., by video conference). They also submit their scores on-line. The scores are discussed until a consensus is reached, after which the results are discussed with the project team. Some organizations are also experimenting with self-managed gates, in which the project team also serves as the gatekeepers. However, this in only used when the risks are relatively low. A variation on this approach is to use gatekeepers that are not part of the normal stage-gate process, thereby providing a type of peer review of the project. Some organizations are also beginning to encourage the project teams to make its own recommendations before the gate meeting. In this way, the actual gatekeepers are viewed as more of a secondary review panel, thus avoiding the necessity of boring down to investigate details.

In addition to gatekeepers, other key roles (or actors) in the MIP include the following:

> *Process owner*—This is the individual responsible for defining and updating the technology stage-gate process, championing its use within MDA, tracking the projects within the process, and serving as a process-related resource to other participants.
>
> *Project leader*—Every process that enters the MIP pipeline will have an assigned project leader. It is this individual's responsibility to manage the project as it flows through the stages and gates. This individual is accountable for project deliverables and coordinating and overseeing the activities of the project team.
>
> *Project team*—This is a cross-functional group that, along with the project leader, is responsible for overseeing the activities carried out during the various process stages. The membership of the team will depend on the nature of the specific project and may change and expand as the project progresses down the pipeline.
>
> *S&T performer(s)*—In most cases, the projects will be executed by organizations outside MDA, either contractors or other governmental organizations. Most likely, one or more individuals from the performing

organization(s) will participate in at least part of the review gate activities, particularly regarding work that has been accomplished or is planned for subsequent stages.

Several new product development consultants and practitioners have identified important attributes or "best practices" that affect the success of stage-gate processes. These keys to success include the following:[11]

Leadership support—Like most changes within organizations, the implementation of a stage-gate process does best when it is supported by top management. In this case, however, such support is not only desirable, it is critical if the process is to become an effective means of generating essential missile defense concepts and technologies. As a minimum, top management needs to participate in the kick-off of the process and be visible and supportive in the various review stages. Having a senior manager serve as an executive sponsor and advocate for the process is also desirable. And last but not least, having senior executives acknowledge and reward those individuals responsible for the success of the process is an important aspect of any type of change management.

Adequate resources—Having available adequate resources for implementing the process and supporting the resulting S&T projects is critical to success. Without adequate resources, quality of execution and team morale suffer, time delays occur, and only low-impact technologies emerge from the process.

An appropriate process design—Although several standard stage-gate processes have been acquired from various consulting organizations, it is important that the process chosen for implementation be tailored specifically to the needs and characteristics of the using organization. "Best practices" used by other organizations are important, but they first need to be subjected to a critical assessment to be sure that they can be properly used in a particular

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[11] Barbara M. Pitts, and L. Michelle Jones, "Successfully Implementing the Stage-Gate™ New Product Development Process," Working Paper No. 18, Product Development Institute, Inc., Ancaster, Ontario, Canada, 2003; R.G. Cooper, and S.J. Edgett, "Overcoming the Current Crunch in New Product Development Resources," Working Paper No. 17, Product Development Institute, Inc., Ancaster, Ontario, Canada, 2003; R.G. Cooper, S.J. Edgett, and E.J. Kleinschmidt, "Optimizing the Stage-Gate Process: What Best Practice Companies are Doing—Part I," *Research-Technology Management*, Vol. 45, No. 3, 2002, pp. 21–27; Cooper, et al., "Optimizing the Stage-Gate Process—Part II;" and A. Khurana, and S.R. Rosenthal, "Towards Holistic 'Front Ends' in New Product Development," *Journal of Product Innovation Management*, Vol. 15, 1998, pp. 57–74.

situation. Thus, each stage-gate process must be customized to meet the using organization's needs prior to implementation. Areas that are particularly troublesome in process design include structuring the "fuzzy front end," establishing appropriate cross-functional teams, and creating and implementing tough decision gates. It is also important that the process design be holistic, in that it provides for the integration of the S&T strategy with the organization's mission and product-development strategies and procedures.

Defined roles and responsibilities—Implementing a stage-gate process requires the coordinated efforts of many people, and it is important that these roles and responsibilities be defined in advance to ensure effective implementation. Of particular importance are the gatekeepers (i.e., decision-makers); the project leaders and teams; and the process manager, the individual responsible for defining, championing, and implementing the process.

Implementation plan matched to organizational situation—Without a clear mandate and visible support from top management for implementing a new planning and management process, it is necessary to adopt a more nonthreatening, "grass roots" approach that will build acceptance among middle managers, technical personnel, and other participants. Such an implementation strategy requires involving the affected stakeholders, along with initial trials and successes that can lead to successful institutionalization of the process. Thus, an effective implementation plan must be both participatory and integrative to achieve sustainable results. And because each organization's culture is different, the implementation plan must also be designed with an eye toward lessons learned from other successful implementations that have been achieved by the organization.

Effective communication—A significant level of effort is invested in designing an appropriate process, and it is important that the insight gained from this effort be communicated to all the participants to increase their knowledge and obtain as much buy-in as possible. Therefore, a communication plan should be part of the implementation strategy.

Focus and discipline—Two of the most common problems encountered with new stage-gate processes are undertaking too many projects and the inability to terminate marginal or underperforming projects. There are many

underlying reasons for these difficulties, particularly regarding the inability to kill projects. These reasons include pursuit of pet projects or those mandated as "must do" by senior management or external organizations, unwillingness to cancel efforts that represent large sunk costs, and lack of effective gating mechanisms to control what flows through the S&T pipeline. A number of techniques can be used to focus the process, such as creating an explicit S&T innovation strategy to set direction and guide activities, applying schemes to establish priorities within stages to determine which projects are within budget limits, and using a portfolio-management process to ensure balance among competing resource demands. In the end, it is far better to adequately fund a few good projects than to attempt to pursue too many efforts that are underfunded and understaffed, and thus unlikely to succeed.

Progress measurement—A few carefully chosen metrics should be selected to measure the progress made in implementing the stage-gate process. These metrics should include tracking implementation milestones against target dates; the number of projects in each stage; dwell times, attrition rates and reasons; progress toward meeting overall process goals (e.g., number of projects by stage, funding levels, and number of successes); and the impact of success stories.

The above summarizes an approach for implementing the MIP technology stag-gate processes within MDA/AS. Such a process would provide several important benefits, including: (1) an effective method for deciding which project to fund; (2) aligning projects with MDA S&T strategies and organizational objectives; (3) establishing guidance on project definition, including scope, desired outputs, integration, and transition of results; and (4) reviewing projects to ensure progress, programmatic fit, and priority. The overall impact of the MIP would be to streamline early-stage S&T activities within MDA/AS while balancing the creative technology and pragmatic applications perspectives.

MDA/AS SCORING MODELS FOR SETTING PRIORITIES

One of the main challenges in planning an S&T program is ranking the project alternatives to determine the highest priority options to be pursued. Scoring models represent an increasingly used decision-making technique that can help support this ranking function.

Traditionally, formal scoring models have not been widely used to rank S&T investment alternatives. For example, here are five common approaches for allocating resources that do not rely on formal scoring models:[12]

- *Squeaking wheel*—Resources are minimized or reduced in all areas, and depending on which area complains the loudest and most insistently, budgets are restored until the funding ceiling is reached.
- *Level funding*—Budget changes are minimized, and the status is quo maintained to the detriment of new initiatives.
- *Glorious past*—Resources are assigned on the basis of past record of achievement.
- *White charger*—The best speaker, department with the best presentation, or last person to brief the decision-maker receives the resources.
- *Advisory committee*—A committee reviews the alternatives and advises the decision-maker on how to allocate the resources.

Although the above methods lack a scientific or objective basis, they are widely used in many organizations. Often such techniques fail to adequately take into consideration the "bottom line" impact of the investments on the organization and its products. Consequently, S&T investments tend to be driven by short-term priorities and pressures and do not address broader long-term needs and opportunities for higher payoffs.

To improve this situation, many organizations have turned to using scoring models as decision-making tools for evaluating and ranking alternative S&T investments. This section of the report addresses the types of scoring models that could be used by MDA/AS in planning and managing its S&T program.

Any decision-making tool must be developed to fit the context in which it will be used. In this case, the scoring model will be employed to rank alternative S&T projects, especially in the early phases of MDA's technology stage-gate process (see separate section describing the MDA Innovation Process). The score a particular candidate project receives from the model will largely determine (or at least greatly affect) whether the project is funded and enters the S&T pipeline. Thus, use of the scoring model would be a

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12 M.J. Cetron, "Technology Forecasting for the Military Manager," in *An Introduction to Technological Forecasting*, Edited by J.P. Marino, Gordon & Breach, London, 1972; M.R. Kirby, and D.N. Marvis, *A Technique for Selecting Emerging Technologies for a Fleet of Commercial Aircraft to Maximize R&D Investment*, SAE Paper 2001-01-3018, 2001.

key part of the review that takes place during MIP Gate 0, the on-ramp for the stage-gate process.

Although scoring models are frequently used for selecting among project alternatives, they represent only one of several approaches.[13] These techniques can be grouped into four categories:

- *Intuition*—Purely intuitive judgment is sometimes used for decision-making, particularly for selecting smaller projects and in emergency or time-limited situations. This approach is generally viewed as the most unreliable except for all but the most routine decisions. Unfortunately, many individuals—including most managers—have an unreasonable faith in their intuition. (Although intuition is not strictly speaking a scoring model, it is included here for comparison purposes.)
- *Rules*—Heuristic rules (e.g., to fund S&T projects that support a major organizational strategy regardless of the intrinsic merit of the project) are easy to employ and are sometimes used to defend decisions. However, such rules inherently interject strong biases in the decision-making process.
- *Decision weighting (i.e., scoring models)*—This approach entails identifying and weighting those factors that are most important to the decision and then scoring the alternative projects in terms of these factors. Those projects receiving the higher scores are given higher rankings.
- *Value analysis*—Systematic, detailed value-analysis techniques are sometimes used to evaluate project alternatives. Although such methods can produce the best decisions, they can be difficult to implement and, if not carefully structured and documented, may not provide transparency into the underlying basis for the decisions.

Table V-3 gives a comparison of the advantages and disadvantages of each technique category.

Table V-3. Pros and Cons of Different Decision-making Approaches
(Source: Modified from Russo and Schoemaker, *Winning Decisions*)

Decision Method	Quality and Reliability	Level of Effort	Transparency
Intuition	Low	Low	Very Low
Rules	Moderate	Low to Moderate	Moderate
Weighting	High	High to Low	Very High
Value Analysis	Very High	Very High	High to Low

[13] J. Edward Russo, and Paul J.H. Schoemaker, *Winning Decisions: Getting it Right the First Time*, Doubleday, 2002.

In general, organizations should use the decision-making approach that provides the highest levels of quality and reliability consistent with the resources available and context of the decision. In selecting projects to enter into an S&T pipeline (or funnel), the specific details of the technology or innovation are usually not defined well enough to apply detailed value-analysis techniques; the necessary data usually do not exist, hence the need for the S&T project. Thus, in the early phases of a technology stage-gate management process, weighting techniques are the most suitable decision-making aid. However, value-analysis methods may be more applicable in later phases of the stage-gate process, when more data become available.

A large number of weighting techniques and scoring models have been developed for evaluating decision alternatives, including the ranking and selection of S&T projects. One of the most widely used techniques is the Kepner-Tregoe decision-analysis method, which was developed in the late 1950s.[14] This method is a systematic procedure for making choices based on the following activities:

1. State the decision to be made.
2. Develop objectives.
3. Classify objectives into MUSTs and WANTs.
4. Weight the WANTs.
5. Identify the alternatives (in this case, S&T projects or technology areas).
6. Screen the alternatives through the MUSTs.
7. Compare (score) the alternatives against the WANTs.
8. Identify adverse consequences.
9. Make the best balanced choice.

Although the process seems detailed, it can be implemented quickly, with relatively little effort. The scoring model is developed and applied in steps 2, 3, 4, and 7.

Applying the Kepner-Tregoe technique to the ranking of potential MDA S&T projects would be fairly straightforward. The objectives and associated weightings need to be developed with the full participation of MDA management, however.

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14 Charles H. Kepner, and Benjamin B. Tregoe, *The New Rational Manager*, Princeton Research Press, 1997.

As an example, the following WANTs objectives (i.e., evaluation criteria) and weightings could be used.[15]

- Project will enable significant performance improvements in an MDA system—Weight 10.
- Likelihood of project technical success is high—Weight 5.
- Project will result in a cost-effective solution—Weight 5.
- Project results can be readily adapted into future systems and concepts of operations—Weight 5.
- Project will face minimal nonmilitary obstacles—Weight 5.

A suitable scoring range would then be defined for each objective and used for evaluating the project alternatives. Each objective would typically have a scoring range of 1 to 10, depending on specified measures or standards. At this stage of project definition, the scoring ranges primarily reflect qualitative indicators. For example, for Objective 1 (potential performance improvement), the scoring range might be from 1 for low performance improvement to 10 for major performance improvement.

The next step is to score each alternative for the objectives using the agreed-upon scales. These individual scores are then multiplied by the objective weights to determine the weighted scores, which are then added to obtain a total weighted score for the project. The total weighted scores are then used as a primary indicator of project ranking.

Table V-4 gives hypothetical example of this type of scoring for several projects that have been discussed by the pilot team.

Table V-4. Example Scoring of Three S&T Project Alternatives

	Objective (Score, Weighted Score)										
	Performance Improvement (weight 10)		Low Risk (weight 5)		Cost-effective (weight 5)		Adaptability (weight 5)		Other Issues (weight 5)		Weighted Total
New Sensors	4	40	8	40	10	50	3	15	10	50	195
New Propellant	2	20	5	25	7	35	8	40	10	50	170
New Booster	8	80	2	10	10	50	10	50	6	30	220

15 This example is derived for the case of evaluating specific technology projects; the same approach, with some modification to the criteria and weights, could also be used evaluate and rank key technology areas or alternative missile defense system concepts. Scoring could be done by a team of individuals, and the results averaged to produce an overall score. MUSTs objectives (e.g., the project addresses an S&T issue) are not discussed in this example.

In this example, the third project, low-cost boost technology for the space-based laser, received the highest total weighted score, and thus would receive the highest ranking recommendation based on its overall total. Typically, the highest ranking projects would be funded in descending rank order until the available funds were exhausted. However, since real-world ranking decisions are based on more than scores, the scoring model only provides an indication of rank and not the final decision by the responsible managers. This point will be discussed in more detail later.

Note that the above example is purely hypothetical, with weights and scores chosen arbitrarily. Also note that in a real-world scoring situation, the scoring ranges would be better defined, and the rationale for the scores given each alternative and objective would be documented to better understand the logic behind the ranking recommendations.

Although the scoring model in Table V-4 provides a means of ranking the projects, it does not take into consideration all issues of importance. In particular, the scoring model does not address the impact the projects (or technologies) can have on other MDA systems.

One way to overcome this issue is to weight the individual projects with respect to their relevancy to the MDA systems, whether being developed or only conceptual. This modification is illustrated in Table V-5, where the various system concepts are weighted from 0 to 10 points based on their importance to MDA. The relevance of each project is estimated, and these weights and relevance factors are then multiplied by the raw score the projects received from the previous model to determine a weighted relevance for each system. These weighted relevance for each system are then added for each project to yield an overall relevance score, which is used to rank the projects.

The data from the example in Table V-5 indicate the highest priority project would be the new propellant project, based on its widespread relevance to a number of MDA systems. As with the earlier scoring example, this case is purely hypothetical, and the data were selected to demonstrate the effect relevance across systems has on establishing priorities. Although this second model addresses additional factors, the necessary information may not be available for the Gate 0 review. Thus, this scoring model method may be more applicable for Gate 1, when the project concept has been better defined and can be more readily evaluated in terms of relevance to other MDA systems.

As the project moves down the stage-gate pipeline, additional information and insight will be developed that will enable the use of more quantitative scoring models. For example, in later stages of the pipeline, it may be possible to quantitatively assess the potential impact of the S&T project versus risks (both technical and implementation), thereby enabling more realistic trade-offs when establishing priorities between project candidates. However, since reliable quantitative information is normally not available in early phases, such advanced scoring techniques are not applicable.

The basic Kepner-Tregoe method (and variations) mentioned above is not the only scoring technique that is used for establishing S&T priorities. Other, more elaborate weighting schemes have also been created. The primary motivation for developing these advanced approaches is to provide more reliable and consistent ways to analyze complex issues and determine relative weights of decision-making objectives.

One of the more important more advanced weighting schemes is the Analytical Hierarchy Process developed by Thomas Saaty in the 1970s. According to its developer, the Analytical Hierarchy Process is

> A method for breaking down a complex, unstructured situation into its component parts; arranging these parts, or variables, into a hierarchic order; assigning numerical values to subjective judgments on the relative importance of each variable; and synthesizing the judgments to determine which variables have the highest priority and should be acted upon to influence the outcome of the situation.[16]

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[16] Thomas L. Saaty, *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World*, RWS Publications, Third Edition, 2001.

Table V-5. Example Scoring of Three Hypothetical S&T Project Alternatives Against IDA Pilot Systems (1 to 3) and Other MDA Applications (4 to 12)

System Application	Weight (0 to 10)	New Sensors (Raw Score 195) Relevancy (0.0 to 1.0)	New Sensors (Raw Score 195) Weighted Relevance	New Propellant (Raw Score 170) Relevance (0.0 to 1.0)	New Propellant (Raw Score 170) Weighted Relevancy	New Booster (Raw Score 220) Relevance (0.0 to 1.0)	New Booster (Raw Score 220) Weighted Relevance
1. BAAM (Buried Autonomous Anti-Missile System)	5	1.0	975	1.0	850	0.0	0
2. UAV (Unmanned Arial Vehicle)	5	0.1	98	0.5	425	0.0	0
3. SBL (Space Based Laser)	5	0.1	98	0.0	0	1.0	1,100
Subtotals			**1,171**		**1,275**		**1,100**
4. ABL (Airborne Laser)	10	0.1	195	0.5	850	0.0	0
5. Ground Based Midcourse	10	0.1	195	0.8	1,360	0.0	0
6. Aegis Ballistic Missile Defense	10	0.1	195	0.8	1,360	0.0	0
7. THAAD (Theater High Altitude Air Defense System)	10	0.1	195	0.8	1,360	0.0	0
8. Arrow	5	0.1	98	0.8	680	0.0	0
9. Patriot PAC-3	10	0.1	195	0.8	1,360	0.0	0
10. MEADS (Medium Extended Air Defense System)	5	0.1	98	0.8	680	0.0	0
11. STSS (Space Tracking and Surveillance System)	10	0.1	195	0.0	0	1.0	2,200
12. RAMOS (Russian-American Observation Satellite)	5	0.1	98	0.0	0	1.0	1,100
Subtotals			**1,464**		**7,650**		**3,300**
Totals			**2,635**		**8,925**		**4,400**

The Analytical Hierarchy Process is important for decision-making in complex situations for two reasons. First, it allows the user to structure problems in an integrated, hierarchical manner and address how individual elements affect the performance of the entire system. Second, it provides a method for the user to establish priority relationships between competing and disparate factors in a logically consistent manner. The Analytical Hierarchy Process enables this function by using matrixes that provide pair-wise comparisons of the properties or features being analyzed. Combined, these two features allow the method to be used to define and evaluate priorities using a top-down, systematic approach and a bottom-up view that provides logically consistent criteria and weightings. These dual properties are particularly useful when trade-offs must be made between conflicting choices that are difficult to compare directly, such as human safety and product performance or environmental consequences and economic impact.

The Analytical Hierarchy Process is mentioned here because it is increasingly being touted as a way to establish priorities in difficult planning situations. But the method it is a complicated decision-making tool that can be very expensive to design and apply. Consequently, it is unlikely that the Analytical Hierarchy Process would be suited for planning early-stage MDA S&T programs. However, under certain circumstances the technique may be applicable to MDA. These circumstances could include analysis and decision-making for complicated architectural and layered defense alternatives, especially during later phases of the stage-gate process.

All of the above should lead the reader to the conclusion that the scoring methods used to assign priorities to S&T project alternatives need to be selected based on where the projects are in the stage-gate process. Regardless of the method selected, scoring models are not a panacea for good decision-making. Although the use of scoring models helps provide a rational decision-making process, several inherent underlying difficulties must be avoided.[17] Occasionally, scoring models are used that do not yield logical or consistent answers or fail to provide enough sensitivity to select among the candidates. This typically means that the problem has not been properly framed or the weightings have not been adequately derived, thus necessitating a redesign of the scoring model. But no scoring method will be perfect because no model can accurately mimic reality, capture all relevant information, or consider all consequences. In the end, decision-making is still

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17 James G. March, *A Primer on Decision Making: How Decisions Happen*, The Free Press, 1994.

a human process, and humans are notorious for behaving differently than predicted by decision theory.

To guard against these difficulties, a number of keys to successful decision-making have been developed.[18] These include the following:

- Use a value creation lens for developing and evaluating opportunities.
- Clearly establish objectives and trade-offs.
- Discover and frame the real problem.
- Understand the operational impacts of the decision.
- Develop creative and unique alternatives.
- Identify experts and gather meaningful and reliable information.
- Embrace uncertainty as the catalyst of future performance.
- Avoid "analysis paralysis" situations.
- Use systematic thinking to connect current to future situations.
- Use dialog to foster learning and clarity of action.

Because the use of scoring models will become an integral and recurring part of the MDA stage-gate process, such techniques will need to well defined and documented. Their use will also require training and discussions between the project champions and the decision-makers. It may also be appropriate to assemble ad hoc review panels of experts to score the project proposals, with the final scoring results being one input used by the gatekeepers that decide whether the project moves to the next stage-gate phase.

Implementation of scoring models into the MDA stage-gate process will require a few person-months of effort to define the models, develop appropriate weights, identify reviewers, and train users. It is assumed that this function would be the responsibility of the individual who serves as the process owner and champion for MDA's stage-gate process. Additional resources would also be desirable for outside support for model development and implementation assistance. The level of resources will depend on the number of models developed.

Recommended Next Steps for MDA/AS

The above material and the data contained in the appendixes represent an initial effort to compile a directory of analytical tools and techniques that could be potentially

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[18] David C. Skinner, *Decision Analysis: A Practitioner's Guide to Improving Decision Quality*, Probabilistic Publishing, Second Edition, 2001.

be used by MDA/AS in planning and managing its S&T program. Collectively, this information should be viewed as a first step in defining appropriate tools. Because the topic is so diverse and rapidly changing, the collection and expansion of similar information should be an ongoing effort in the future.

In addition to this ongoing maintenance of a tool knowledge base, efforts should also be undertaken to:

- *Designate one or more tool focal points*—This is such an important area for MDA/AS that it warrants the designation of one or more individuals to serve as focal points for championing the development and use of the types of tools discussed in this report.
- *Rank the tools and techniques*—Each tool will need to be ranked in terms of its relevance to MDA/AS's needs. This ranking will need to take into consideration related tools already being used by MDA and similar techniques discussed in other IDA Phase II tasks.
- *Develop a tool implementation plan*—Based on the above rankings, an implementation plan needs to be developed for the highest priority tools, including estimates of resource requirements. (Specific implementation steps for the three example tools—stage-gate processes, scoring models, and modeling and simulation—are discussed in previous sections of this report.)
- *Implement tools*—Proceed with tool implementation, as appropriate.

VI. MODELING AND SIMULATION

John Meyer and Paul Collopy

INTRODUCTION

Modeling and simulation (M&S) is widely recognized as a tool that often plays a vital role in R&D. This chapter examines how M&S can be used within MDA/AS for S&T program planning, execution, and management, and what actions are needed to move forward in this area. It includes a specific example of a combined M&S and scoring method being developed as part of this IDA task for evaluation of missile defense concepts and technologies: The Technology Value Model.

M&S is the development and use of various models and simulators to investigate, understand, or provide experimental stimulus for both existing systems that cannot undergo experimentation due to resource, security, safety, or other limitations or for conceptual systems and technologies that do not exist. A "model" is a mathematical, physical, or procedural representation of a system, component, technology, entity, phenomenon, or process. A "simulation" is a method of implementing a model over time. A simulation brings the model to life and shows how a particular object or phenomenon will behave. There are several different types of simulations, including:

- Virtual simulations involving totally synthetic (both electronic and physical) representations of war-fighting systems and environments patterned after actual operations and equipment.
- Constructive simulations that involve real people providing inputs into a simulation that carries out those commands by exercising artificial models of systems and people.
- Live simulations where military operations are carried out using live forces and weapons systems on test or exercise ranges to simulate actual operating conditions.

USES AND BENEFITS OF M&S IN S&T PLANNING AND MANAGEMENT

M&S has been used extensively for decades in many areas beyond S&T program planning, execution, and management, including engineering design, manufacturing planning, user training, business exercises, macroeconomic and financial analysis, and

war gaming. Military interest in M&S involves such diverse topics as requirements definition, systems interoperability, test and evaluation, battle-space management, logistics, and training. Military M&S is typically used to:

- Reduce time to field new or upgraded systems.
- Increase military worth of fielded systems while simultaneously optimizing force structure, doctrine, tactics, techniques, and procedures.
- Enable concurrent fielding of systems with their training devices.
- Reduce total ownership costs and sustainment burden for fielded systems throughout their service lives.[1]

To address this broader military context of M&S during the past few years DoD has embraced the concept of simulation-based acquisition.[2] DoD has defined it as "an acquisition process in which DoD and industry are enabled by robust, collaborative use of simulation technology that is integrated across acquisition phases and programs."[3] The concept of simulation-based acquisition has an even broader set of goals than those mentioned earlier:[4]

- A dramatically improved acquisition process enabled by the application of advanced information technology.
- Earlier and better informed decisions and reduced risk by more accurate and comprehensive assessments of designs, manufacturing, support and employment.
- The early optimization of system performance versus total cost of ownership.
- Lower total ownership cost and standards-based reuse of information and M&S software to minimize their costs.
- More optimal investments enabled by system-of-systems mission area assessments.
- Enduring collaborative environments, reusable and interoperable tools, and supporting resources.

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1 *Simulation & Modeling for Acquisition, Requirements and Training (SMART) Reference Guide*, Army Modeling and Simulation Office, April 2001.

2 *Roadmap for Simulation Based Acquisition, Joint Simulation Based Acquisition Task Force*, under the Acquisition Council, DoD Executive Council for Modeling and Simulation (EXCIMS), December 1998.

3 *Simulation-Based Acquisition Definition*, DoD Modeling and Simulation Acquitition Council, August 2000.

4 Ibid.

- Automated near-real-time sharing of relevant information among all personnel with a need to know by use of distributed product descriptions through a common technical architecture and open, commercial data-interchange standards.

The tremendous breadth of the simulation-based acquisition concept is illustrated by the "to-be" architecture shown in Figure VI-1. The S&T portion of the process model (in the lower left of the figure) plays a limited but important part in the concept.

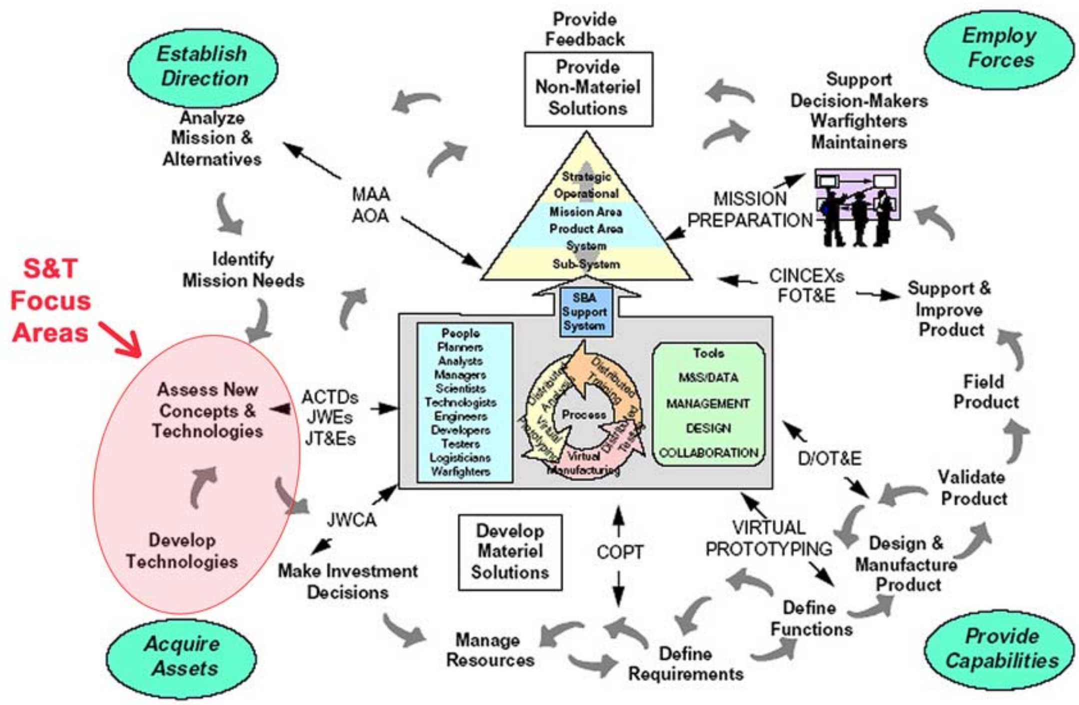

Figure VI-1. Simulation-Based Acquisition "To-Be" Process Model and Focus of S&T Activities

(Source: Adapted from "Roadmap for Simulation Based Acquisition," Joint Simulation Based Acquisition Task Force, Acquisition Council, DoD Executive Council for Modeling and Simulation (DoD EXCIMS), December 1998.)

In addition to the overall role S&T plays in the simulation-based acquisition process model, the reader should also be aware of the various types of models that are employed in M&S. In the simulation-based acquisition context, models are viewed as part of a hierarchy, as shown in Figure VI-2. Although there are no strict differences between types of models shown in the hierarchy, they do tend to differ considerably in a number of factors, including such issues as objectives, fidelity, number of entities

incorporated in the model, and cost, as shown in Table V-6, which compares some of the differences between S&T models and product engineering models.

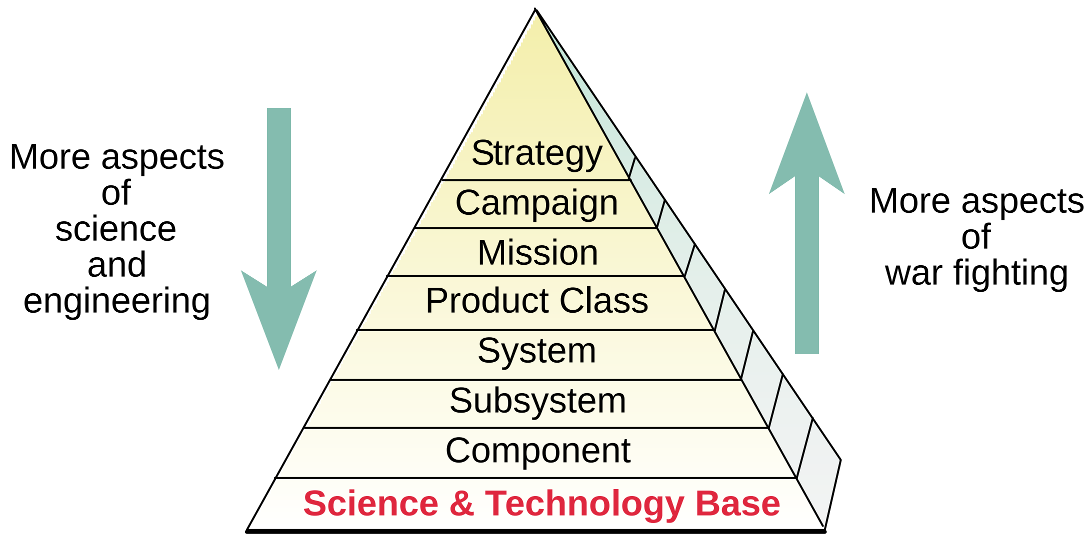

Figure VI-2. Simulation-Based Acquisition Model Hierarchy

(Source: Modified from "Roadmap for Simulation-Based Acquisition," DoD Executive Council for Modeling and Simulation (EXCIMS))

It is also important to note that the simulation-based acquisition hierarchy implies the potential for compatibility and integration up and down the hierarchy. Thus, systems models could conceivably be assembled from models of subsystems, which in turn could be constructed from models of components, which could be based on physics-based models of the underlying technologies. Although such a hierarchical "object-oriented" approach to M&S is far from being a reality, it is one of the major goals underlying this acquisition concept and offers a powerful justification for moving in this direction in the future.

Table VI-1. Differences between S&T Models and Engineering Models

	S&T Models	**Engineering Models**
Objectives	1. Analysis of alternatives 2. Sensitivity analyses 3. Identification of key variables 4. First-order estimates of performance and cost	1. Design trade-offs 2. Refine requirements and design details 3. Definition of subsystems 4. Performance and cost verification
Fidelity	Low to moderate	High
Cost	Low to high	High
Availability	Very limited (custom)	Limited (may use common approaches)
Commercial Tools	Few	Many

In addition to variations between model types, it is also important to note differences between who develops and owns the models, as shown in Figure VI-3. Thus,

to truly integrate the models within the simulation-based acquisition hierarchy will require considerable collaboration between the various owners and stakeholders involved in the process. Because most M&S efforts have been undertaken independently in the past and thus represent many differing approaches and instantiations, this integration within the hierarchy and across a system's life cycle will represent a major challenge for many years to come.

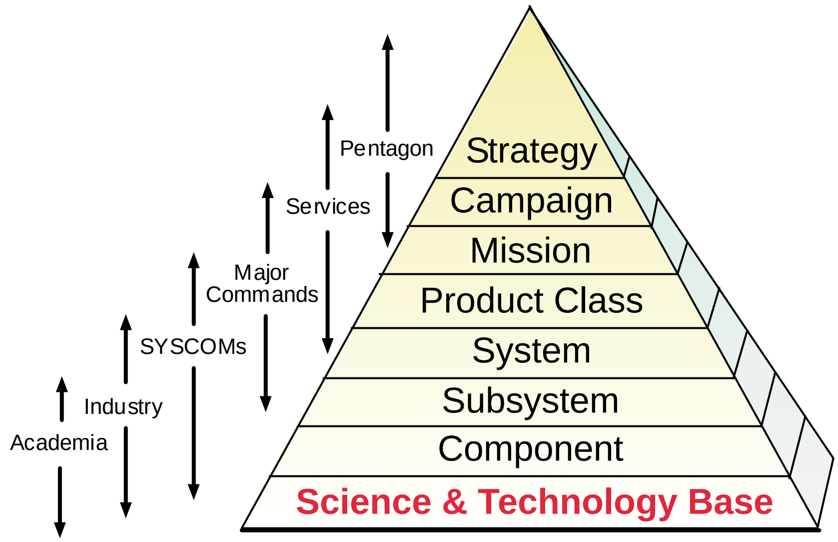

Figure VI-3. Model Ownership

In terms of project execution, M&S is becoming a key element in undertaking research efforts. Research projects generally represent an iterative optimization process involving (1) hypothesis or concept synthesis, (2) experimentation and evaluation, and (3) decisions about the validity of the hypothesis or concept. However, because of the expense and time required to perform the experiments and evaluation testing, M&S is being increasingly used, as a separate step in the process, to investigate the hypothesis or concept prior to experimentation. (This was certainly true of the concepts explored during the Pilot task of the MDA Phase II study, during which relatively simple models were extensively used to evaluate the feasibility of the concepts and identify key issues that needed to be addressed in follow-on research.)

In addition to assessing feasibility and performance of a new concept or technology, M&S can also be used to:

- Determine and visualize the feasible research, design space, and application envelope for a new concept or technology.

- Identify risks and significant “showstoppers” that need to be carefully examined to ensure feasibility.
- Investigate likely costs of developing, producing, and operating the solution.
- Address issues such as interoperability and user interfaces.
- Explore other important topics, such as producibility, reliability, maintainability, logistics, and training, if appropriate.
- Provide virtual prototypes and technology modules that can be used in larger simulations and integrated computer-aided exercises.
- Serve as an important mechanism for collaboration between technology developers and users.

The above M&S capabilities provide research users with the following important benefits:

- Cost savings due to a reduction in the need for physical prototypes and testing.
- Reduced experimental design and analysis time.
- Increased understanding of the concept or technology and its underlying phenomenology.
- The ability to assess more options.
- Reduction and management of risks.

In addition to the above direct benefits, research users have also experienced the following indirect benefits from M&S:[5]

- Generation of useful surprises or knowledge about the technology, concept, or applications.
- Greater insight into organizational needs and priorities.
- Better understanding of the consequences of S&T management decisions.
- Improved innovations due to the more extensive interaction among appropriate stakeholders.

M&S Trends

M&S technology and applications are far from being static. Some of the trends taking place include the following:[6]

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5 M. Shrage, *Serious Play: How the World’s Best Companies Simulate to Innovate*, Harvard Business School Press, 2000.

- Development of models incorporating advanced techniques from such fields as complexity and chaos theory, neural networks, agent-based models, response surface methods, and genetic algorithms to permit analysis of complex, nonlinear problems.
- Use of data mining, data farming, and knowledge discovery tools that aid analysis of large amounts of data generated from simulations and use of advanced visualization techniques that convey useful information from data.
- Increasingly pervasive use of M&S throughout all phases of a weapon system's life cycle in an integrated manner to achieve simulation-based acquisition.
- Sharing and reuse of models and data, among domestic users, programs, industry, and Services and on an international basis.
- Development and use of secure interoperable environments and standards, such as the Defense Modeling and Simulation Office's High Level Architecture (now IEEE standard 1516), to help bring about the rapid federation of models and joint simulations.[7]
- Increasing cost effectiveness of M&S based on continued advances in computer performance and reduced cost of hardware and software.
- Emergence of relevant commercial tools, such as MatLab, Excel, M&S languages, and some of the integrated modeling environments discussed earlier.
- Growing experience base for M&S of large, complex systems.

Collectively, these trends suggest that M&S technology, applications, and infrastructure are moving forward rapidly and that important developments can be expected in the next few years.

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6 L. McGlynn and S. Starr, "SIMTECH 2007 … and Beyond," Future Modeling and Simulation Challenges, NATO Modeling and Simulation Group Conference, Breda, Netherlands, 12–14 November, 2001.

7 The High Level Architecture is a general-purpose architecture for simulation reuse and interoperability. It was developed under the leadership of the Defense Modeling and Simulation Office to support reuse and interoperability across the large numbers of different types of simulations developed and maintained by the DoD. The High Level Architecture Baseline Definition was completed on August 21, 1996. It was approved by the Under Secretary of Defense for Acquisition and Technology (USD(A&T)) as the standard technical architecture for all DoD simulations on September 10, 1996. Julien Scharl and Dimitri Mavris, "Development of an Object Oriented Vehicle Library for Automated Design Analysis," SAE Paper 2001-01-3034, 2001.

Difficulties in Applying M&S in S&T Applications

Although M&S offers great potential in S&T program planning, execution and management, the technology also raises a number of issues.

For example, in modeling and simulation of new concepts, a trade-off must be made between model accuracy (i.e., fidelity) and efficiency (i.e., development costs and computing requirements). For technologies and concepts that are early in their S&T development, detailed information and models are unlikely to exist, and thus new models will need to be developed or existing models will need to be adapted to the new concepts. However, development of high-fidelity models at this stage of concept maturity is rarely possible due to lack of data or understanding of the underlying phenomenology and prohibitive resource requirements (time and cost). Development of detailed models based on finite-element analysis and computational fluid dynamics, for instance, can be very expensive. Similarly, parametric models may not be applicable because the new technologies and concepts, by definition, lie outside the range of conventional solutions.

One promising solution to this dilemma is the development and use of "meta models."[8] Meta models are "models of models" that represent efficient replacements of the basic physics-based models. Meta models seek to form a more compact representation of the functional relationships between model inputs and outputs. The meta modeling process represents a functional approximation of the underlying physics-based model. Many techniques exist for creating such meta models, from linear regression and response surface methods to neural networks.

In multidisciplinary analysis problems—which represent most new concepts or technologies—separate multiple meta models corresponding to each engineering or technical discipline would be required. The term "discipline" refers to both the classical engineering sense (e.g., aerodynamics) but also to other aspects such as producibility. Most likely, the underlying physics-based models would require different inputs and may even operate on different computing platforms. Thus, some type of integration environment would be needed to facilitate the use and interaction of the multiple meta models. Several companies have developed integration environments for this purpose,

8 Ibid.

including Engineous Software's iSight system[9] and Phoenix Integration's Model Center.[10]

Other difficulties in using M&S techniques for S&T applications include the following:

- Understanding the limitations of the models—A model is by definition not reality, and every model has its Achilles' heel. Understanding the assumptions used in constructing the model and the limitations and risks they introduce into the results of the simulation is an important factor in S&T decision-making.
- Bugs, flaws, and errors in the model—Because models often contain bugs, flaws and errors, it is important that they undergo some type of verification, validation, and accreditation (VVA) before their results are taken as correct.
- Lack of standard models—As mentioned earlier, detailed models are not likely to exist before they are needed in particular S&T applications. Sometimes this occurs because of a lack of agreement among users about what such models should contain and how they should be constructed, thereby necessitating reinvention of the model each time it is needed. In other cases, there is a lack of knowledge of the underlying scientific basis on which to create an appropriate model.

Notwithstanding these difficulties, M&S will surely become more important in S&T applications in the future.

M&S within MDA/AS

The above sections have addressed the use of M&S in research in general. However, for MDA/AS, M&S is particularly relevant because MDA's systems are

- Large, complex, and expensive to develop, procure, and operate.
- Unique, with limited legacy data and complex, often qualitative measures of effectiveness.
- Difficult and expensive to physically test.
- Complex "systems of systems" that often behave in difficult-to-predict ways.
- Based on many underlying technologies that are changing at a rapid rate, in some cases more rapidly than the time it takes to develop and field the system. Moreover, many of the advanced concepts MDA will be considering in the

9 www.engineous.com.

10 www.phoenix-int.com.

future will be based on new technologies with a limited understanding of the underlying phenomenology.

- Being applied in a geopolitical context in which the threats they are designed to counter are not stable.

For all of the above reasons, M&S should become more widely used within MDA as a tool for evaluating new systems concepts, subsystems, components, and technologies. The question then becomes, “How does MDA/AS apply this technology to its needs?”

To answer this question, the IDA Technology Assessment Pilot experimented with different types of models and simulations in the process of identifying innovative new concepts for missile defense that could serve as a basis for defining a long-term S&T program.[11] The definition and analysis of each concept involved some type of modeling and simulation to establish the preliminary feasibility of the concept and to identify the underlying design issues and technologies that will have the greatest effect on the concept’s performance and viability.

These models and simulations were custom developed as low-cost analysis tools because suitable off-the-shelf tools were not available. An MDA/AS toolkit consisting of suite of basic models and simulation environments would have been useful, and such an M&S toolkit would undoubtedly prove to be a valuable asset to MDA and its contractors in the future. A brief literature search showed that some models already exist for space and missile applications.[12] Some of the potentially relevant models are summarized in Appendix D. Undoubtedly, other relevant models are available from proprietary and commercial sources. In addition, numerous existing models address related areas, such as command-and-control systems, atmospheric conditions, and integrated battle management.

The IDA Technology Assessment Pilot also experimented with developing a more robust M&S tool for assessment of technologies and concepts. This tool—The Missile Defense Technology Value Model—is summarized in the next section.

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11 Van Atta et al, “Results of a Technology Assessment Pilot Project for MDA.”

12 Since no analysis has been undertaken about the relevancy of these models, it is unclear to what extent they could be useful to MDA/AS in the planning and management of an S&T program. They are presented here only to illustrate the breadth of existing capabilities.

M&S EXAMPLE: THE MISSILE DEFENSE TECHNOLOGY VALUE MODEL

The Missile Defense Technology Value Model uses attributes of technologies to assess their value. Technologies are evaluated by comparing the value of a ballistic missile defense system (BMDS) when it incorporates the technology with the value of a baseline BMDS without the technology. The difference is the gross value of the fielded technology. Adjustments are made for the time and cost required to develop the technology and the risk that the technology will not work. The result is the net value of the technology. Technologies can be ranked as investment opportunities based on their net value.

The core of the model is a mathematical representation of a BMDS. This tool is important beyond the immediate purpose of technology evaluation. The value model can assess whether one candidate missile defense system design is better than another. That is, it formalizes the notion of *better* with regard to missile defense system design. Any attempt to design the *best* missile defense require a sound notion of what it means to say that one design is better than another. Thus, the value model (or a functional equivalent) is a prerequisite to creating the best possible missile defense system.

For example, the value model can serve as the objective function for optimizing the conceptual design of a missile defense system. That is, optimization becomes the search for the highest value system, as assessed by the value model. Trade studies can use the value model to assess alternatives. The trade option that leads to the highest valued system, per the value model, is the preferred alternative. More important, in the detailed design phase, optimization objectives for each component can be derived in a straightforward manner using the value model. The result is distributed optimal design, which is distinctly different from the state-of-the-art specification flow-down process that repeatedly leads to systems that are overweight and over cost during detailed design.[13]

All these applications (concept optimization, trade study evaluation, and distributed optimal design) are possible with the Missile Defense Technology Value Model. However, the specific goal of this particular model is technology evaluation. The Missile Defense Technology Value Model describes technology in terms of performance and cost metrics to deduce measures of benefit and cost that are then combined to yield

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[13] Paul D. Collopy, "Economic-Based Distributed Optimal Design." AIAA Paper 2001-4675, American Institute of Aeronautics and Astronautics, Reston, Va., 2001.

net economic value. It scores technologies in a way that is objective, repeatable, consistent, and transparent:

- *Objective*—Value model scores are based on performance and cost metrics that, if the technology were in production, could be physically verified.
- *Repeatable*—The value model is essentially a deterministic mathematical function. Unlike Dephi techniques, quality function deployment, or other methods that depend on a group of people arriving at a consensus, the value model will always give precisely the same score to a technology with the same metrics.
- *Consistent*—If any good metric is increased, the score from the model will never decrease. Thus, when comparing two technologies, if one is the same or better on every metric, it will have the same or better score.
- *Transparent*—When one technology outscores another, the reasons for the scoring difference can be easily understood in terms of differences in the technologies' metrics.

The value model characterizes a technology by a set of metrics. Technologies that use the same metrics are grouped together into technology buckets. For example, booster rocket structural technologies are characterized by their impact on rocket mass ratio and cost. All technologies include technology readiness level, probability of successful development, and cost of development as metrics. A technology's metrics are directly used to in the value model to assess the value of the technology. Below is an example of a technology template to input the metrics for technologies in a single bucket, kill vehicle flight control.

Kill Vehicle Flight Control

Name	*Value*	*Description*	*Units*
Designation			
Designation			
Performance			
Dead Miss		Mean miss distance for ballistic target	m
Dead Accel		Maximum acceleration reqd for Dead Miss	m / sec^2
Live Miss		Mean miss distance for maneuvering target	m
Maneuver		Maneuver ratio required for live miss	none
Sensor Lag		Sensor lag assumed in performance metrics	sec
Readiness			
TRL		Technology Readiness Level	see table
Cost			
Development		Cost of SDD through IOC	$ 000 000

Figure VI-4. Example of Technology Template

Kill chains separate the process of intercepting the target into a series of steps, all of which are necessary for successful interception. A probability of success is associated with each step, and the probability of intercepting the target (probability of kill) is the product of all the step probabilities. Although a more complex relationship between step probabilities and probability of kill can be accommodated in the model, it has not been necessary in the prototype.

Most of the cost of the interceptor can be associated with steps in the kill chain. Therefore, each kill chain step calculates a step probability and a cost. The system kill probability and system cost are, roughly, the product of the step probabilities and the sum of the step costs.

Figure VI-5 shows the kill chain for the BAAM system used for the prototype value model and kill chains for other BMDS layers. (More detail on the BAAM concept appears in the companion volume on the Technology Assessment Pilot Project.) The black dots are the kill chain steps for the concept. Note that because many steps are common to many different systems, the prototype model has already developed many of the necessary modules for value models for other missile defense concepts.

	Boost phase intercept	Airborne laser	Pulsed excimer laser	BAAM	Midcourse intercept	Terminal intercept	Rapidly deployable interceptor
BAAM deployed before launch				•			
Ground / sea interceptor deployed in kill zone	•				•	•	
Aircraft / satellite stationed in kill zone		•	•				
BAAM deployed in kill zone				•			
Deployment rockets based in kill zone							•
Launch detected	•	•	•	•	•	•	•
Low altitude tracking (below horizon)	•	•		•			•
Off-board high altitude tracking	•				•	•	•
Decision to intercept	•	•	•		•	•	•
Target discrimination					•		•
Deployment to interceptor kill zone							•
Interceptor boosted to target	•			•	•	•	•
On board tracking	•	•	•	•	•	•	•
Tracking laser illuminating target		•	•				
Beacon laser illuminating target		•	•				
Weapon laser on target		•	•				
Weapon laser dwell time sufficient		•	•				
Laser damage defeats attack		•	•				
Kill vehicle maneuvers to intercept	•			•	•	•	•
Interceptor defeats attack	•			•	•	•	•

Figure VI-5. Kill Chains for Different BMDS Systems Concepts

The Missile Defense Technology Value Model is implemented as a Microsoft Excel spreadsheet. The bulk of the model is devoted to calculating the net value of a BAAM system in service. When a technology is input into the system, quantitative metrics of the technology change attributes of the system and therefore change its net value. The change in system net value is the gross value of the technology to the system.

As explained below, technologies are evaluated under 10 different scenarios, each representing different hostile attacks. Scenarios are characterized by the value of the asset threatened by the missile in terms of the lives at risk, the missile trajectory, and physical aspects of the missile as a target. Scenarios are implemented as separate columns in the model spreadsheet. Each scenario calculates probability of kill (the probability of a single interceptor defeating one target missile) and interceptor unit cost.

Probability of kill and unit cost are combined into a cost-per-kill metric. Together with the asset value, cost per kill determines the net value of the system. Each scenario is then weighted by the probability of it actually occurring. The weighted net values are summed to give the overall net value of the system. The difference between this overall value and a reference value is the gross value of the technology. This is adjusted for technology development to yield the net value of the technology, which is the ultimate technology assessment.

The first step in the model is determining the value of the threatened asset. The asset is characterized by the number of deaths anticipated in the scenario. The deaths are translated into dollars. Military and civilian deaths are considered equivalent in this conversion. Next, the minimum number of BAAM emplacements is determined, based on the spread of threat trajectory azimuths from the specific threat location. For example, North Korean missile threats to the continental United States spread over an azimuth of about 70°. The actual number of interceptors deployed would also depend on the number of threat missiles to be simultaneously launched and the cost per kill of the interceptor. Next, the launch-detection process is modeled, yielding the probability that the launch is detected and the time required for detection. This time is added to the time required for fire control (there is no external decision loop in the BAAM system) to yield the time delay between target launch and interceptor launch.

The next series of steps characterize the interceptor. First, the interceptor trajectory is determined by simultaneously solving for the point of intercept and the standoff distance between the target launch and the interceptor emplacement. The delay between target and interceptor launch is the input to the iteration. Once the trajectory is determined, the kill vehicle velocity at intercept is determined. The kill mass is then sized based on the kinetic energy required for kill. This sizes the kill vehicle, which, taken with the trajectory, sizes the interceptor booster. Cost of the interceptor is inferred from the size of the components.

The next step determines the probability of the kill vehicle defeating the target missile. The last step in examining the system operation assesses the cost and probability of success of deploying the BAAM system prior to launch. This is done last because the size of the missile and standoff distance from the target launch site are already determined.

Probabilities of success from each step are combined into an overall probability of kill, and cost of components is rolled up into an interceptor unit cost. These parameters for a one-on-one engagement are combined into a cost-per-kill metric that is directly used, with the asset value, to calculate the net value of a many-on-one (or, in some scenarios, many-on-many) engagement. From the net value of the system in each scenario, the overall net value of the system is determined, and the gross value of the technology is calculated. The model corrects this gross value to a net present value of the technology investment opportunity. Considerations are the technology readiness level, its probability of success, and the cost required to develop the technology.

In three areas, considerable work was done to establish a rigorous foundation for the equations and coefficients used in the value model:

- *Cost per kill*—A theory has been developed for combining the probability of an interceptor defeating a target missile with the cost of the interceptor to yield a summary cost per kill metric. Together with the value of the asset under attack, cost per kill directly yields the net value of the ballistic missile defense system.
- *Scenarios*—To establish the value of the assets that might be attacked by hostile missiles, a set of representative scenarios has been developed using different types of conflicts, different classes of missiles, and different types of warheads.
- *Threat missiles*—Threat missiles have been characterized for each of the attack scenarios.

We wish to evaluate an interceptor characterized by unit cost, s, and the probability that it will kill a target missile, p_k. Interceptors can be launched in squadrons. A squadron attack of n interceptors is described by the probability tree in Figure VI-6:

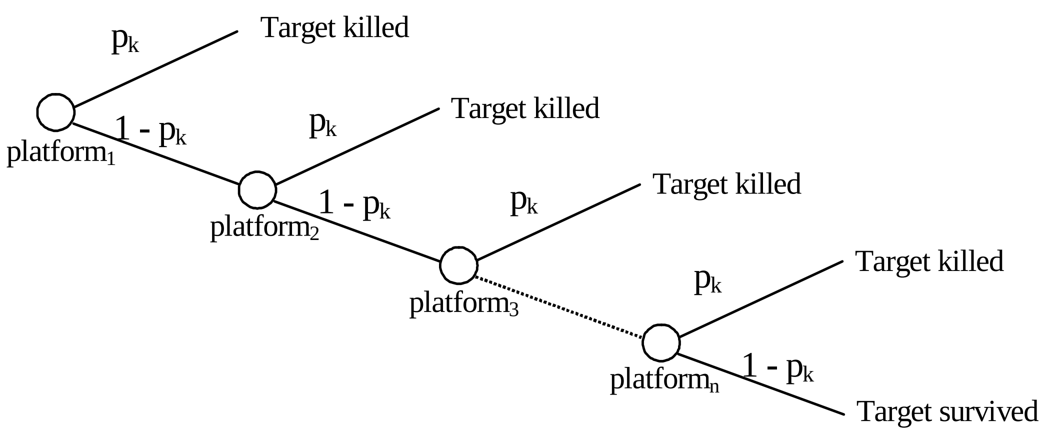

Figure VI-6. Probability Tree for Squadron Attack

Note that the interceptors are launched essentially simultaneously, not in a shoot-look-shoot manner. This can be appropriate within a layer of missile defense, particularly boost-phase defense, but may not apply to a multilayer system of systems.

Attacks are assumed to be probabilistically independent. Each node represents the attack of one interceptor on the target missile. Every upper branch describes an instance where the target is killed. The target only survives the squadron attack if it survives the attack by every interceptor. This outcome is reached only by following the lower branch

leaving each node. The probability that the target survives is the product of the independent probabilities on each of the lower nodes.

If the value of the assets that would be destroyed by the enemy missile is *V*, and the interceptor unit cost is *s*, the net value of the attack is the expectation of the value of attacking the target missile minus the cost of all the interceptors. The most effective squadron is one where *n*, the number of interceptors, is chosen to maximize the net value of the attack. This would find the best balance between the cost of the interceptors and the probability of destroying the target.

It is interesting to note that the expected value of the optimal attack depends only on the asset value and the cost per kill. It turns out that the system with the lowest cost per kill, when used optimally, yields the greatest net value, no matter what the value of the protected asset is. Therefore, if a missile-defense system is designed to minimize cost per kill, it will provide optimal value. This is not true of traditional formulations of cost per kill.

Our value-modeling effort employs a limited set of threat scenarios (15) as a basis for evaluating the potential contribution of technology developments coming out of the Pilot Technology Assessment effort (Table VI-2). These scenarios are designed with a view toward spanning the space of relevant missile defense challenges, while also focusing attention on the set of challenges deemed most likely. They can also serve as a basis for formulating a time-phased implementation plan aimed at providing growing capability against the most daunting challenges in the mission space.

Table VI-2. Technology Value Model Scenarios

Scenarios 1-4	New York City attacked with [1 or 3] single-warhead SCUD B missiles fired from 320 km away in the Atlantic Ocean, carrying a payload of either a [10 kt nuclear warhead or 700 kg Sarin]with a circular error probable (CEP) of 3 km and no spin stabilization of the warheads. *Death toll: Nuclear: 110,000 Chemical: 30,000*
Scenario 5	New York City attacked with two MIRVed (multiple independently targeted reentry vehicle) SS-18, carrying ten 500 kt warheads, fired from 7,000 km away in Russia, with 10 decoys with similar ballistic coefficients as the warheads, 50 mylar balloons, and 20 kg of chaff. *Death toll: 8,000,000*
Scenarios 6-7	The major cities on the U.S. West Coast—San Diego, Los Angeles, San Francisco, and Seattle—as well as the U.S. interceptor base in Alaska, each attacked near-simultaneously with [2 or 10] missiles each, fired from 10,000 km away in China, with each missile carrying four 200 kt nuclear warheads and employing 10 decoys with similar ballistic coefficients as the warheads, 50 mylar balloons, 20 kg of chaff with CEP of 2 km. *Death toll: 2 missiles per city: 1,800,000; 10 missiles per city: 9,000,000*
Scenarios 8-9	From 3,500 km away, North Korea launches a single-warhead missile at Andersen Air Force Base on Guam. The missile carries a 20 kt nuclear warhead and [no countermeasures or employing 5 decoys with similar ballistic coefficients as the warheads] with CEP of 4 km. *Death toll: 10,000*
Scenarios 10-13	Tokyo attacked with [2 or 20] single-warhead missiles fired from 1,200 km away in North Korea. Each missile carries a [(20 kt nuclear warhead or 700 kg Sarin], with no countermeasures. *Death toll: 2 nuclear: 100,000; 20 nuclear: 1,000,000* *Chemical: 2 chemical: 26,000; 20 chemical: 260,000*
Scenarios 14-15	[Central Command (CENTCOM) headquarters in Qatar or Tel Aviv] attacked with two single-warhead SCUD B missiles fired from 300 km away (CENTCOM) or from 1,300 km away (Tel Aviv) in Iran. Each missile carries a payload of a 10 kt nuclear warhead (CENTCOM) or 200 kg Anthrax (Tel Aviv) with no countermeasures and a CEP of 1 km. *Death toll: CENTCOM: 8,000 Tel Aviv: 135,000*

Analyses of the missile-defense problem focus on three critical challenge dimensions:

- *Threat size*—The number of missiles/warheads.
- *Threat location*—Uncertainty as to the location/range from which the missiles may be fired.
- *Threat sophistication*—The complexity of countermeasures employed.

A recent RAND report[14] represented these dimensions in Figure VI-7 below.

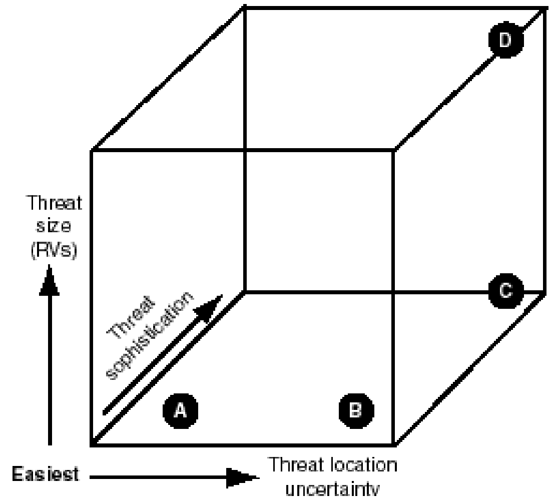

Figure VI-7. Dimensions of the ballistic missile threat space

In addition, for the purposes of value modeling, we need to specify the potential targets of an attack and the type of warhead being carried, because these will affect the consequence (negative value) of failing to intercept a particular missile/warhead aimed at a particular target.

In 2000, the CIA released an unclassified version of its National Intelligence Estimate titled *Foreign Missile Developments and the Ballistic Missile Threat through 2015.*[15] That estimate cited the following central threats to the United States:

- Medium or short-range missiles launched at U.S. cities from the sea.
- Long-range missiles with nuclear or chemical warheads, launched from North Korea or China at regional allies or the west coast of the United States.
- Medium and short-range missiles launched from Iran or Syria, with chemical warheads or possibly nuclear warheads, in the future, targeting U.S. interests and forces in the region.

The estimate did not indicate the relative likelihood of these threats emerging or being realized. As for terrorist threats, the estimate considered that such attacks would most likely be delivered by means other than missiles. With these assumptions as general guidance, the specific scenarios in the table below were used for purposes of analysis.

14 David C. Gompert and Jeffrey A. Isaacson, "Planning a Ballistic Missile Defense System of Systems: An Adaptive Strategy," RAND Issue paper IP-181, 1999.

15 http://www.cia.gov/nic/pubs/other_products/Unclassifiedballisticmissilefinal.pdf.

The American Physical Society report on boost-phase intercept is used to realistically characterize the threat in an unclassified environment.[16] Different target missile designs are assumed for each scenario, with the missile sized to the range required in the scenario. Missiles are assumed to follow optimal Keplerian ballistic trajectories. In boost phase, the missiles execute gravity turns from a vertical launch. Target missiles are assumed to have a specific impulse of 270 seconds and a booster mass ratio of 90%, consistent with a medium technology, low-cost kerosene and liquid oxygen propellant. Acceleration at launch is 1.5 g for short-range missiles (less than 1,000 kilometers) and 1.0 g for longer range missiles. Thrust is constant throughout each stage burn. All targets are two-stage missiles with a 1 metric ton warhead.

The essence of economic evaluation of a missile defense system is the trade between the cost of the ballistic missile defense system and improvement in the probability of defeating enemy missiles. Given scenarios that project casualty rates for enemy missile attacks, the trade boils down to dollars versus lives. How much should be spent to protect a large number of people from death at the hands of a political enemy? Both economic assessments of the impact of terrorist attacks and society's willingness to invest in a response to such attacks reveal that the relationship between dollar value and lives lost is not linear. For this model, the value of life is captured by the exponential curve in Figure VI-8. For a very small number of lives, the value is $50 million per life. For very large casualties, the value approaches $3 million per life. This figure is based on the norm used in U.S. courts for civil awards in liability cases, which is just under $2 million, plus a 50% addition to account for destruction of infrastructure in addition to the loss of life. The other significant assumption relates to the value of time: a real discount rate of 5% is used to account for the disadvantage of long periods of technology development.

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16 Lamb and Kleppner, 2003.

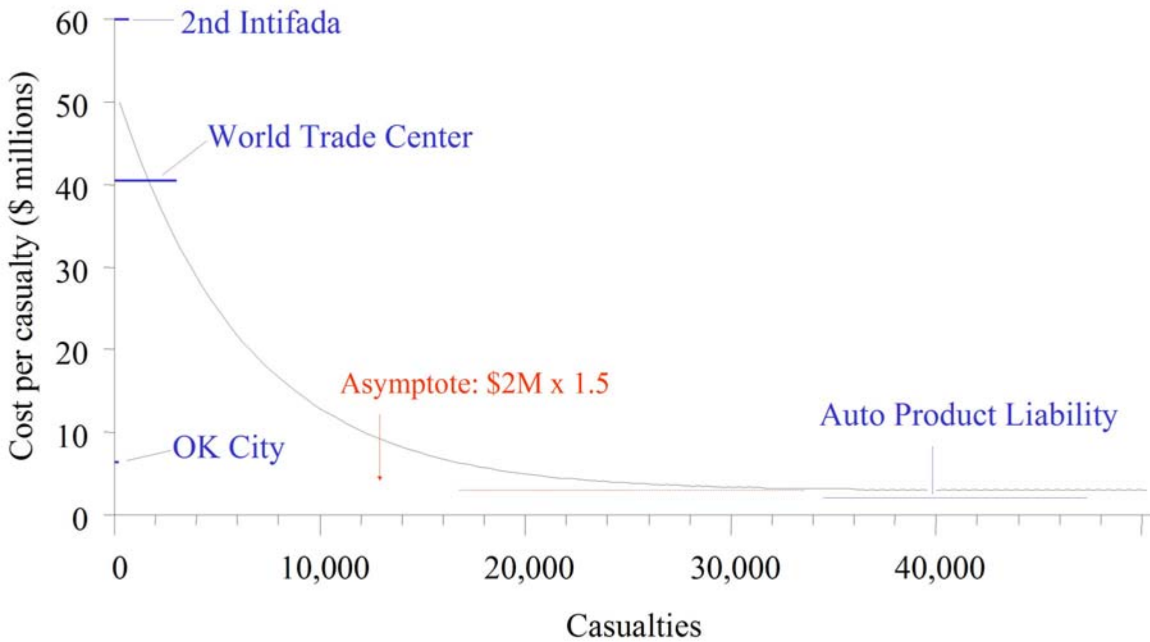

Figure VI-8. Kill Chains for Different BMDS Systems Concepts

Quantitative Analysis with the BAAM Technology Value Model

Although the current study did not include a technology search to obtain metrics of specific technologies which could be evaluated, the Technology Value Model nevertheless provides some broad direction for promising areas of S&T investment.

For example, some performance attributes are clearly of minor importance. A 10-second improvement in specific impulse of the interceptor rocket would be a very challenging goal based on progress made over the last two decades. Furthermore, it would only provide a $5 million increase in value to the BAAM weapon system. Likewise, a 1% decrease in the drag coefficient of the rocket's aerodynamic shell provides only $0.1 million of value.

Rocket mass ratio (ratio of fuel mass to total rocket mass) is a more promising research area. Increasing the mass ratio from 85% to 86% is worth $1 billion. The baseline interceptor rocket weighs about 100 kilograms. A 1% improvement in mass ratio corresponds to reducing the weight of the structure in the missile by 1 kilogram.

A common design issue is the trade between weight and manufacturing cost. This trade determines whether exotic materials should be used to reduce weight. The value model suggests that for the 100 kilogram baseline interceptor, a $2 million increase in manufacturing cost corresponds to a $1 billion loss in system value. Therefore,

expending up to $2 million in manufacturing to reduce the structural weight of the interceptor by 1 kilogram would be a positive trade. BAAM is very much in the realm of exotic structural material applications. Although the value of technology improvements (the $1 billion figure) is sensitive to scenario assumptions, the trade factor (1 kilogram ~ $ 2 million) is fairly independent of them.

Often the value of a technology is very sensitive to the current state of the technology. Figure VI-9 below shows the value of the BAAM system versus the probability that the BAAM unit, dropped from the delivery aircraft, will emplace in the ground in such a way that the interceptor can be effectively launched. If the probability of success is zero, the overall system has no value. As the probability exceeds 20%, the sensitivity of system value to probability of emplacement (the slope of the curve) is greatly reduced. However, the overall value of BAAM is very large: $1.8 trillion in the baseline case. Even when the probability of emplacement is 35%, the value of an increase of 1% is over $1 billion. As the probability reaches 90%, the value of an additional 1% improvement is reduced to $10 million, which would make it a marginal S&T prospect.

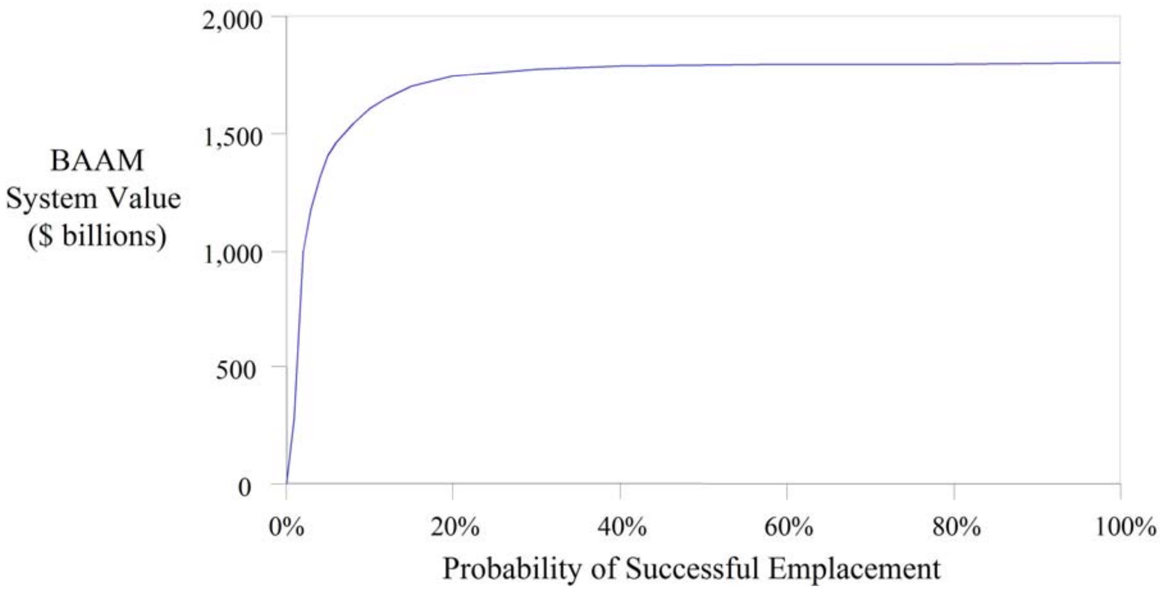

Figure VI-9. Value of the BAAM System Versus Emplacement Probability

The sensor used by BAAM to detect target missile launch is assumed to have a baseline sensitivity of 4 standard deviations—that is, the mean of the signal exceeds the mean of the background noise by 4 standard deviations of the background noise distribution. Increasing the sensitivity by 1 more standard deviation is worth $600 million, a good S&T candidate.

Decreasing the time required for sensing the target missile launch, or any activity on the time line between target missile launch and interceptor launch, is worth $30 million per second, a possible S&T candidate. Another marginally attractive candidate is decreasing the sensor lag in the hit-to-kill vehicle, which is worth $10 million for every 10 millisecond improvement.

The Technology Value Model can be used to examine new intercept methods, such as the Explosively Formed Projectile (discussed in the companion volume on the Technology Assessment Pilot Project). The Explosively Formed Projectile, is an alternative to a simple hit-to-kill vehicle, expels a large number of small particles at very high speed toward the target. The Technology Value Model shows that the best Explosively Formed Projectile system is superior to simple hit-to-kill when the probability of hit to kill destroying the target is less than 30%. Hit to kill is always superior when it has more than 40% chance of killing the target. Between 30% and 40%, the results depend on the scenario.

The Explosively Formed Projectile requires a smaller amount of mass to actually hit the target because the projected particles have higher velocity. However, only a small fraction of the projected mass (at best, only 0.5%) actually strikes the target. The net result is that system requires an interceptor payload 20 to 50 times larger than the simple kill vehicle. The effect on the size of the interceptor rocket motor and the size of the entire deployed BAAM package is similar.

Because the Explosively Formed Projectile makes the rocket much larger, technologies that reduce rocket size become much more important. A 10-second increase in specific impulse is worth $300 million in an Explosively Formed Projectile system versus $5 million in conventional hit to kill. Similarly, a 1% improvement in mass ratio is worth $400 million under the Explosively Formed Projectile system versus $10 million for the baseline system.

In summary, the Technology Value Model provides quantitative insight into the relative importance of different avenues of S&T investment, as well as the ability to evaluate specific technology opportunities. The Buried Autonomous Anti-Missile Defense System Technology Value Model is a prototype. The Technology Value Model can be extended to address other missile defense concepts. With application in practice it can also be matured and better adapted to users in MDA/AS. The Technology Value Model can be extended to a design value model, an objective function for optimal

conceptual design, or an aid to evaluating trade studies. It can form the basis for a distributed optimal design approach to full system development.

For a technology value model, the greatest need is a trustworthy and rigorous process for estimating the time, cost, and risk for developing specific technologies. Research into historical trends of progress of actual technologies through technology readiness levels versus time and expenditures could create a database from which technology development could be forecast based on progress through readiness levels and spending to date. Such a technology development forecasting system would have wide applicability.

Conclusions and Next Steps

This chapter has provided an overview of how M&S can be used within MDA/AS for S&T program planning, execution, and management, and it has provided a specific example in the Missile Defense Technology Value Model. To increase the beneficial use of M&S in planning, execution, and management of MDA's S&T program, we recommend the following actions:

1. Establish a focal point within MDA/AS to coordinate relevant M&S activities. Such a focal point could be an internal individual or team or an outside supplier of M&S expertise.
2. Collect, document, and evaluate relevant models in terms of their applicability to MDA/AS needs. Organizations that should be contacted include the following:
    - Defense Modeling and Simulation Office.
    - Service M&S offices.
    - DoD Modeling and Simulation Information Analysis Center.
    - Space Users Group of the DoD Modeling and Simulation Analysis Center.
    - DoD Modeling and Simulation Resource Repository.
    - BMD Simulation Support Center.
    - BMDO M&S Resource Repository.
    - American Institute of Aeronautics and Astronautics.
    - Military Operations Research Society.
    - Simulation Interoperability Standards Organization.
    - Society for Computer Simulation International.

- Other organizations involved in the development and application of relevant models, including technology developers, FFRDCs (e.g., IDA), and organizations such as the Aerospace Systems Design Laboratory at Georgia Tech.

3. Identify M&S voids that need to be addressed. This could be done by establishing an overall M&S architecture or conceptual reference model for MDA applications, crating specific M&S functionalities, validation and verification of new or existing models, and coordination among ongoing or planned M&S efforts being undertaken by other organizations.
4. Fill the voids.
5. Facilitate the use of M&S for specific S&T applications managed by MDA/AS.
6. Consider creating an integrated MDA conceptual design and analysis M&S environment or toolkit and related infrastructure for use in S&T program planning, execution, and management.
7. Measure the impact that M&S has on MDA/AS's S&T program, and report this impact to senior MDA and DoD management.
8. Extend the Technology Value Model to
   - Address other missile defense concepts (with application in practice it can also be matured and better adapted to users in MDA/AS.)
   - Serve as a design value model, that is, an objective function for optimal conceptual design or an aid to evaluating trade studies. In this form, it can be used to coordinate distributed design teams.
   - Incorporate historical information on the time, cost, and risk for developing specific technologies to create a database from which technology development could be forecast based on progress through readiness levels and spending to date.

Modeling and simulation technology can play an important role in MDA/AS S&T planning and management by reducing research cost and time and enabling the exploration of more advanced concepts and emerging technologies.

ACRONYMS

ARL	Army Research Laboratory
AWSIM	Air Warfare Simulation
BAAM	Buried Autonomous Anti-Missile System
BART	Battle Area Regions Threatened
BMDS	Ballistic Missile Defense System
C2W	Command and Control Warfare
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Radar
CAPS	Commander’s Analysis and Planning Simulation
CATT	C2W Analysis and Targeting Tool
CECOM	Communications Electronics Command
CENTCOM	Central Command
CEP	Circular Error Probable
COSMOS	C4ISR, Space and Missile Operations Simulation
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
EADSIM	Extended Air Defense System
FFRDC	Federally Funded Research and Development Center
GIANT	GPS Interference and Navigation Tool
GLEEM	Global Positioning System End-to-End Model
GOTChA	Goals, Objectives, Technical Challenges, Approaches
GPS	Global Positioning System
IMAS	Integrated Modeling and Analysis Suite
INS	Inertial Navigation System
ITW/AA	Integrated Theater Warning and Attack Assessment
JICM	Joint Integrated Contingency Model
JSIMS	Joint Simulation System
JWARS	Joint Warfare System

LTAS	Laser Threat Analysis System
M&S	Modeling and Simulation
MASC	Model for Analysis of Sensor Coverage
MDA	Missile Defense Agency
MDA	Missile Defense Agency
MDA/AS	Missile Defense Agency/Advanced Systems (Director)
MDST	Missile Defense Space Tool
MIP	MDA Innovation Process
MIRV	Multiple Independently Targeted Reentry Vehicles
NASA	National Aeronautics and Space Administration
NASM	National Air and Space Model
NUCSS	USSPACECOM Communications Simulation System
OODA	Observe, Orient, Decide, and Act (loop)
OSD	Office of the Secretary of Defense
PSM	Portable Space Model
R&D	Research and Development
RDT&E	Research, Development, Test, and Evaluation
S&T	Science and Technology
SBMCS	Space Battle Manager Core System
SEAS	System Effectiveness Analysis Simulation
SMAT	Satellite and Missile Analysis Tool
SPAAT	Sensor Platform Allocation Tool
SPAWAR	Space and Naval Warfare Systems Command
SST	Spacecraft Simulation Toolkit
STAMP	Strategic and Theater Attack Modeling Process
STORM	Strategic and Theater Operations Research Model
STK	Satellite Tool Kit
SWOT	Strengths, Weaknesses, Opportunities, Threats
TRL	Technology Readiness Level
UAV	Unmanned Aerial Vehicle

APPENDIX A
VIRTUAL LABORATORY CASE STUDIES

ROCKWELL SCIENTIFIC AND BOEING PHANTOM WORKS

In 1996, Rockwell International Corporation sold most of its defense and aerospace business units to the Boeing Company. At that time, a special transition agreement was executed between the two corporations, providing for continued R&D support to Boeing by Rockwell's central research laboratory, the Rockwell Science Center (known after 2001 as Rockwell Scientific Company). The agreement provided for 3 years' guaranteed funding at a prescribed level, with automatic renewals unless Boeing gave 1 year's notice of cancellation. The collaboration has been a successful one, with both sides benefiting. Rockwell Scientific has enjoyed a stable source of funding and a window into a large defense business and its government customers. Boeing has enjoyed access to world-class research capabilities by paying a relatively low fixed fee, without having to take on large human resource commitments. Perhaps the most important testimony to the collaboration's success is that 8 years later, at the time of this writing, the agreement is still in force.

The relationship between Boeing and Rockwell Scientific has been a close one, with Rockwell Scientific acting as a virtual laboratory division of Boeing's Phantom Works. Technical areas of collaboration include advanced materials, high-speed electronics, high-data-rate wireless systems, multimodal integrated displays, and various fields of information science. Boeing tends to use Rockwell Scientific as a source of unique capabilities rather than as a pool of extra manpower for routine tasks. Were this not true, the relationship would probably not have lasted.

A high-ranking executive at Boeing oversees the relationship, and Rockwell Scientific has a full-time Boeing Program Director. Contacts between the two organizations are both broad and deep. Division directors at Rockwell are tightly coupled to executives at Phantom Works, as are individual scientists to their technical counterparts. Projects are initiated by mutual agreement and are collaboratively planned. Informal reviews on most projects occur weekly, with formal reviews occurring

quarterly. Relationships between Rockwell Scientific and Boeing are, on some occasions, closer than relationships between different parts of the Boeing company itself.

Potential conflicts of interest do arise. On occasion, Rockwell Scientific and Boeing Phantom Works may compete with each other for government contracts, although this is usually avoided. Of more concern is that Rockwell Scientific has a close relationship with Rockwell Collins company's defense division, a direct competitor with parts of Boeing's defense businesses. Further complicating the relationship, Boeing's commercial airplane division is the largest customer of Rockwell Collins' commercial business, which in turn also has a close relationship with Rockwell Scientific. The most difficult conflicts arise when Collins' defense business competes directly with Boeing in a government procurement, and Rockwell Scientific is required to support both. Such conflicts are managed through continual vigilance and the construction of strict firewalls when necessary. The agreement between Rockwell Scientific and Boeing specifies that Boeing owns all intellectual property arising from projects it funds. Thus, scientists in the same research group at Rockwell Scientific who ordinarily collaborate closely are enjoined from discussing specific projects with each other when some are supporting Boeing and others are working for Collins.

There are a number of reasons for the success of Rockwell Scientific as a virtual laboratory division of Boeing Phantom Works, the most important of which are the following:

- High-level executive attention to the relationship on both sides.
- Stable multiyear funding, enabling long-term collaboration.
- The existence of unique capabilities at Rockwell Scientific that augment and complement Boeing's internal capabilities.
- A proactive approach to preventing conflicts of interest.

THE ARMY RESEARCH LABORATORY ADVANCED DISPLAYS FEDERATED LABORATORY

An example of a long-term virtual laboratory structure created by an agency of the United States Government can be found in the Army Research Laboratory (ARL) Advanced and Interactive Displays Federated Laboratory (Displays FedLab).[1] A $30M basic research effort running from 1996 to 2001, its goal was to develop new

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[1] M.S. Vassiliou, "The ARL Displays FedLab: A Partnership between Industry, Government, and Academia," *Proc. 2000 IEEE Aerospace Conference*, 2000, pp. 521–529.

technologies in visualization, collaborative planning, human-computer interaction, and related areas.

The Displays FedLab began as a consortium led by Rockwell Science Center (now known as Rockwell Scientific), then a major corporate research laboratory. The consortium also included Rockwell's Collins business unit, a leading manufacturer of commercial and military avionics systems; the University of Illinois at Urbana-Champaign’s Bekmann Institute, an internationally renowned center of excellence in multimedia and visualization technologies; industrial partners MCNC and Sytronics; and North Carolina Agricultural and Technical College. The consortium members accepted central direction from ARL and functioned for 6 years as virtual laboratory divisions. The Displays FedLab was one of three Federated Laboratories formed by ARL in 1996, the other two being focused on advanced sensors and advanced telecommunications.

The FedLab concept was arguably the most important of a series of management reforms undertaken by ARL in the mid 1990s, in response to tremendous budget and mission pressures. ARL concentrates on basic and applied research, as well as weapons analysis. Its primary customers are the research, development and engineering centers of the Army Materiel Command. ARL strives to achieve preeminence in key areas of science and engineering relevant to land warfare; to foster a close relationship with Army users and a partnership with the rest of the defense community; and to interact extensively with academia, industry, and other government laboratories.[2] In many ways, ARL’s role is similar to that of a corporate laboratory in a large company, supporting the various R&D and advanced development centers in the corporation’s business units by creating, importing, evaluating, and adapting technology.[3]

Since the early 1990s ARL has operated under extreme pressure on its resources. The total budget dropped from nearly $600M in FY1992 to $356M in FY1998, with a concomitant decrease in headcount.[4] During the same period, the Army’s senior leadership assigned ARL an entirely new and very substantial mission. After Desert Storm, then Army Chief of Staff General Sullivan directed that Army Materiel Command develop the technology necessary to “digitize the battlefield.” This directed the Army to

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2 National Academy of Sciences, *Army Research Laboratory Technical Assessment Board: 1998 Assessment of the Army Research Laboratory*, Washington, D.C.: National Academy Press, 1999.

3 E.A. Brown, *Reinventing Government Research and Development: A Status Report on Management Initiatives and Reinvention Efforts at the Army Research Laboratory*, Report ARL-SR-57, Army Research Laboratory, 1998.

4 Ibid.

> devise systems that will enable real-time situational awareness for battlefield commanders at all levels. Such awareness demands wireless, near-instantaneous communication vertically and horizontally, with total fusion of all relevant information (intelligence, weather, and terrain data, logistics information, etc.), which must then be displayed in a readily comprehensible format.[5]

ARL was given the responsibility of conducting the basic R&D in support of this mission and transferring the technology to the Communications Electronics Command (CECOM) Research Development and Engineering Center, which would then design and field the systems.

The FedLab concept was one result of these challenges and pressures. By joining in a long-term partnership with several industrial and academic entities to attack a broad relevant technology area, ARL could access a range of talent that would be practically impossible to grow in house. Since the "digitization of the battlefield" required technology development in areas where commercial industry and certain academic locations were already very advanced, the FedLab could serve as a mechanism for ARL to extract significant leverage.

Although in the Federated Laboratory structure the industrial and academic partners received funds from the government, the arrangement was significantly different from the usual contractual research relationship. The primary difference was that the government entity in question, in this case ARL, was not a simple funding agency but an active participant in the research, collaborating with and directing its virtual divisions. The FedLab was funded by a relatively new government instrument, the Cooperative Agreement.[6] This authority was granted to the Department of Defense under 10USC2358.[7] The Cooperative Agreement allows a highly collaborative and substantial relationship between the government and the vendor. ARL and its partners could jointly plan and execute research, jointly report results, and jointly redirect work as required. The Cooperative Agreement should not be confused with the Cooperative Research and Development Agreement, a different instrument created by the Technology Transfer Act of 1986 to facilitate commercialization of technologies developed in National Laboratories.[8] There is no relationship between these two types of arrangements.

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5 Ibid.

6 Ibid.

7 http://ww.darpa.mil/cmo/pdfs/2358.pdf.

8 G. Tassey, *The Economics of R&D Policy*, Quorum, Westport, Conn., 1998.

The Displays FedLab was managed by a committee of representatives from all members, reporting directly to a program manager at ARL. The management committee and ARL jointly prepared annual research plans, working to ensure the relevance of the research to customers in the Army. Great care was taken to see that resources were committed to the technology transition process. Although the program was funded under Section 6.1 of the Defense Research and Engineering budget, a stream of Section 6.2 transition funds was also separately injected to aid in technology transfer to ARL's government customers (primarily CECOM). The three FedLabs held an annual symposium in which they presented reviewed papers and demonstrations highlighting the previous year's work. In addition, the FedLabs were reviewed annually by the Army Research Laboratory Technical Assessment Board, composed of experts from the National Research Council.[9]

From a technical point of view, the Displays FedLab was a significant success, delivering new technologies in collaborative planning, multimodal integrated display systems, virtual and augmented reality systems, and many others to the Army for further development and in some cases for immediate use. However, could the same results have been achieved through simple contracting without the management overhead? Probably not: simple contracting would not have led to the same level of integration in the systems ultimately delivered to CECOM. Was the FedLab then a success as a virtual laboratory? The answer is a qualified yes. As noted above, it is difficult to imagine ARL hiring and maintaining such a broad range of world-class talent internally. It is equally difficult to imagine ARL obtaining the same level of sustained collaboration in a simple contracting structure. However, the Displays FedLab fell short of the ideal of a virtual laboratory in a number of ways:

- Funding was unstable and inconsistent; budget uncertainty led to destructive conflicts and gaming among the members.
- Centrifugal forces were strong. That is, individual consortium institutions often shamelessly pursued their own divergent interests without regard for the goals of the enterprise as a whole. Some of them occasionally did "end runs" around the consortium and attempted to market their own activities to ARL as if it

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9 National Academy of Sciences, *Army Research Laboratory Technical Assessment Board: 1997 Assessment of the Army Research Laboratory,* Washington, D.C.: National Academy Press, 1998; Also NAS (1999)

were simply a contract monitor. They were sometimes successful in these efforts, distorting the consortium's integrated plans.

- Most research staff members at Consortium institutions were not working full time on the program and thus did not fully "report into" ARL as members of a true virtual division.
- Staff rotation policies from the consortium institutions to ARL and vice versa were not followed to the degree originally envisioned (in the end, no one could be forced). The researchers in the various member institutions did not interact as much as they could have. More important, not enough of their knowledge was captured and used by ARL.
- In some cases, ARL did not have enough internal capability to engage fully with the virtual divisions, leading to some working independently. The reason for having the virtual divisions in the first place was so that ARL could draw on capabilities it did not have; however, without some minimal dedicated capability, ARL often could not successfully interact with the virtual divisions.

Overall, though, the FedLabs can probably be counted as a successful experiment. The Displays FedLab, along with its two sister consortia in sensors and telecommunications, received the "Hammer Award" in 1998 from the U.S. Vice President's National Partnership for Reinventing Government, as a new, effective, and efficient way for the Government to fund and participate in R&D. In 2001, a new round of multiyear Federated Laboratories (renamed "Collaborative Technology Alliances") was funded.

APPENDIX B
NANOTECHNOLOGY NETWORKING OPPORTUNITIES

The field of nanotechnology—the process of manipulating matter at the atomic scale—has expanded greatly over the past few years and has the potential of providing significant technological benefit. Current government programs in nanotechnology that constitute the National Nanotechnology Initiative are being coordinated through the Nanoscale Science, Engineering and Technology Subcommittee of the National Science and Technology Council. The Council was established in 1993. It is a cabinet-level council that coordinates S&T policies and programs across the government and attempts to establish national goals for federal S&T investments.

Member organizations of the Nanoscale Science, Engineering and Technology subcommittee are listed below:

Chair: M.C. Roco, National Science Foundation
Executive Secretary: J.S. Murday, Naval Research Laboratory

Members:
Department of Agriculture
Department of Commerce
Department of Defense
Department of Energy
Department of Homeland Security
Department of Justice
Department of State
Department of Transportation
Department of the Treasury
Environmental Protection Agency
Food and Drug Administration
Intelligence Community
National Aeronautics and Space Administration
National Institutes of Health
National Institute of Standards and Technology
National Science Foundation
Nuclear Regulatory Commission
Office of Management and Budget
Office of Science and Technology Policy

Table B-1 shows federal funding for nanotechnology over the past 3 years FY01 and FY02 funds are actual expenditures, the funding for FY03 are estimates, and FY04 are budget requests. Of the total funds shown in FY03, $32 million ($29 million in NASA's total and $3 million in the U.S. Department of Agriculture) are in associated programs. The rest of the funding is directly in support of nanotechnology development. All funding shown is in millions of dollars.

Table B-1. Federal Funding for Nanotechnology

Agency	FY01	FY02	FY03	FY04
Department of Defense	163	227	243	222
Department of Energy	88	91	139	197
Department of Justice	1	1	1	1
Department of Transportation	0	2	2	2
Environmental Protection Agency	5	5	5	5
National Aeronautics and Space Administration	22	46	51	31
National Institutes of Health	40	41	43	70
National Institute of Standards and Technology	33	38	44	62
National Science Foundaion	150	199	221	249
Department of Agriculture	2	2	3	10
Total Funding	504	652	752	850

Table B-2 breaks down DoD funding by organization and funding category. Again, the funds shown are in millions of dollars. The FY01 and FY02 funds are actual expenditures, the FY03 funds are estimates, and the FY04 figures are budget requests.

Table B-2. DoD Funding for Nanotechnology

Organization	FY01		FY02		FY03		FY04	
	6.1	6.2+	6.1	6.2+	6.1	6.2+	6.1	6.2+
DDR&E/DUSD	30	0	26	0	28	0	28	0
DARPA	34	21	52	62	49	93	36	81
Army	8	1	18	9	18	11	20	10
Air Force	8	10	11	9	9	4	12	6
Navy	46	5	38	2	30	1	28	1
Total	126	37	145	82	134	109	114	108

A significant portion of the 6.1 program in OSD is part of a Defense University research initiative on nanotechnology. New DARPA programs include nanostructures in biology, quantum information, and molecular electronics. The Air Force's basic research activities are in nanocomposites; self-assembly and nanoscale processing for the realization of 3-D optical and electronic circuitry; highly efficient space solar cells; nanoenergetics; nanostructures for highly selective sensors; nanoelectronics, nanomagnetics, nanophotonics; and nanostructured coatings, ceramics, and metals. The Army is allocating $10M of the basic research funds for a University Affiliated Research Center—Institute for Soldier Nanotechnologies. The purpose of this center is to develop nanometer-scale science and technology solutions for the soldier. The center will

emphasize revolutionary materials research to improve advanced soldier protection and survivability capabilities. The Naval Research Laboratory is establishing a nanoscience institute. Scheduled to open this summer, the institute will enhance multidisciplinary thinking and critical infrastructure. A recent thrust in nanotechnology research is to counter the current terrorist threat. Nanoscience is showing great promise for an array of inexpensive, integrated, miniaturized sensors for chemical, biological, radiological, and explosive agents; protection against agents; and nanostructures that neutralize agents.

Government-sponsored investments in nanotechnology are not limited to the United States Worldwide these investments totaled approximately $3 billion in FY03. In addition to the $700 million in the United States, Japan is investing $800 million, Western Europe $600 million, and other countries, including China and Korea, an additional $750 million. Information about industry investments in the United States is difficult to acquire because they are considered competition sensitive. The best estimates are amounts roughly equivalent to the federal investment.

Currently, 20 government-sponsored centers in the U.S. have a nanotechnology focus; all are associated with universities:

National Science Foundation

Nanoscale Science & Engineering Centers

Nanoscale Systems in Information Technology	Cornell University
Nanoscience in Biological & Environmental Engineering	Rice University
Integrated Nanopattering & Detection	Northwestern University
Electronic Transport in Molecular Nanostructures	Columbia University
Science of Nanoscale Systems & Device Applications	Harvard University
Directed Assemble of Nanostructures	Rensselaer Poly Institute

Nanobiotechnology, Science & Technology Center	Cornell University

Material Research Science & Engineering Centers

Nanoscopic Materials Design	University of Virginia
Nanostructures Materials	UC Santa Barbara
Semiconductor Physics in Nanostructures	Univ Oklahoma & Arkansas
Nanostructured Materials in Interfaces	Univ Wisconsin Madison
Quantum & Spin Phenomena in Nanomagnetic Structures	Univ Nebraska Lincoln
Research on the Structure of Matter	Univ Pennsylvania

Department of Defense

Institute for Soldier Nanotechnologies	MIT
Center for Nanoscience Innovation for Defense	UC Santa Barbara
Nanoscience Institute	Naval Research Laboratory

NASA

Institute for Cell Mimetic Space Exploration	UCLA
Institute for Intelligent Bio-Nanomaterials & Structures for Aerospace Vehicles	Texas A&M
Bio-Inspection, Design and Processing of Multi-functional Nanocomposites	Princeton
Institute for Nanoelectronics & Computing	Purdue

Additional centers are planned. For example, the DOE will be funding the establishment of five centers valued at approximately $85 million apiece in nanotechnology.

Given this interest and potential opportunities, one question remains: Will nanotechnology help MDA meet its mission? Discussions with Dr. Murday of the Naval Research Laboratory and Executive Secretary of the National Nanotechnology Initiative

provided some insight into the following areas of nanotechnology research that will have an impact on MDA.

> *Electronics*—Microelectronics is driven by miniaturization which leads to increased performance. The process of miniaturization is characterized by Moore's law, which says that the number of transistors on a chip doubles every 18 months. Many predicted ends to Moore's law have come and gone, but it appears that the industry will be reaching its limits in silicon-based devices over the next 10 years. Nanotechnology and molecular electronics may provide the ability to manufacture devices that have dimensions of 10 nm and lower. This is the focus of a DARPA's Molecular Electronics program. Smaller and faster electronics will lead to smaller and faster systems that are and will remain of vital importance to MDA.
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> *Advanced Materials*—Carbon nanotubes—sheets of graphite rolled up with their edges connected to form a cylinder—hold the promise of extremely high tensile strength inclusions for nanocomposites, structural beams for nanomachines, and possibly conductors for nanoelectronics.[1] This will lead to significant improvements in strength-to-weight ratios of structural materials. In addition, materials research will lead to improved sensors, energetic materials, batteries, solar cells, and fuel cells. All of these technologies will be of vital importance to MDA.

One can quickly reach the conclusion that MDA should be involved in nanotechnology research. An initial step would be to start to interact with the current activities underway to coordinate the various government programs. The first of these is the Nanoscale Science, Engineering and Technology Subcommittee of the National Science and Technology Council. As discussed above, this is an interagency working group whose mission is to coordinate government research in nanotechnology. Key government players of the National Nanotechnology Initiative that meet monthly include:

- Dr. Mihail Roco and Dr. Thomas Weber from the National Science Foundation
- Dr. J.S. Murday from the Naval Research Laboratory
- Dr. Clayton Teaque from the Department of Commerce
- Dr. Gernot S. Pomrenke form the Air Force's Office of Scientific Research
- Dr. Clifford Lau from the Office of the Secretary of Defense
- Dr. Richard Lareau from Homeland Security

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1 "Materials Engineering with Nature's Building Blocks," *AMPTIAC Quarterly*, Volume 6, Number 1, p. 31.

- Dr. Minoo Dastoor from NASA

Legislation authorizing the National Nanotechnology Initiative is working its way through Congress. As recommended by an NRC report, the legislation will call for an external panel to review the initiative. A President's Council of Advisors on Science and Technology panel is being formed to accomplish that review. In addition, this year's Defense Authorization Act has required that DoD develop and submit to Congress a strategic plan for nanotechnology by March 2004. Fiscal year 2004 language will be requiring the same from the other agencies. Dr. Cliff Lau from OSD is currently revitalizing DoD working groups to develop the Department's strategic plan in nanotechnology, which will have to be coordinated with the other agencies.

A series of "Grand Challenge" workshops are underway and will continue through next January in support of these efforts. This process and the development of a DoD Strategy would provide MDA an excellent opportunity to become engaged. It is my understanding that MDA was invited to participate in these DoD and interagency activities when they were initiated about 5 years ago, but declined.

There is reason and opportunity for MDA to become actively involved in the current nanotechnology research underway in DoD and the other government agencies. It is considerably more difficult to determine what should be the extent of that involvement. To answer this question MDA will have to decide what areas of nanotechnology provide the greatest opportunities to help meet its mission. Once these have been identified, the level of existing funding already committed, organizations performing research in these areas, and the direction of the existing research can be used to determine MDA's level of participation and with whom they need coordinate.

Suggested next steps:

1. Continue to gather information on nanotechnology and research underway.
2. Become involved in the activities underway to develop a strategic plan for DoD's nanotechnology research and possible the National Science and Technology Council activities.
3. With Dr. Murday from the Naval Research Laboratory, prepare a briefing outlining current levels of research, areas that will affect MDA, and opportunities for cooperation within DoD and the other agencies. This briefing could be provided to Gary Payton.

APPENDIX C
ANALYTIC TOOLS

Table C-1. Management Tools

Tool	Description	Purpose	Approach	Comments
Early stage-gate process	A structured framework for managing R&D projects, where the stages represent the phases the project must progress through, and the gates refer to review points where the progress and future direction of the project are reviewed against a set of criteria.	Stage-gate systems are used to: (1) guide decisions on which project to fund; (2) align projects with R&D objectives; (3) provide guidance on project definition, including scope, desired outputs, integration, and transition of results; and (4) review projects to insure progress, programmatic fit, and priority.	The technique is implemented by: 1. Establishing appropriate stages, gates, and review criteria to support the organization's research activities. 2. Designation of suitable project teams, decision-makers ("gate keepers"), and documentation requirements. 3. Creation of an implementation plan. 4. Measurement of progress and impact.	Care must be taken when applying the stage-gate process to early S&T stages so as to encourage innovation and to effectively facilitate the "fuzzy front end" of research and concept development. Discipline must be exercised to focus the process on the highest priority projects and ensure that marginal or underperforming projects are terminated.
Benchmarking and performance metrics	A set of tools and methods for evaluating the products, services, and work processes of organizations that are recognized as representing best practices.	Used to improve business processes and products to increase performance and better satisfy customer needs.	Can involve a variety of approaches: 1. Industry group measurements. 2. "Best practice" studies. 3. Cooperative benchmarking. 4. Competitive benchmarking.	Need to define and focus on critical processes and performance issues. Benchmarking is also sometimes used to compare the performance of technologies or products from different sources.

Tool	Description	Purpose	Approach	Comments
Portfolio management	A technique used for allocating resources among various categories of projects. This method is sometimes used in conjunction with stage-gate models to manage projects.	This technique is used to: 1. Select high value projects. 2. Achieve the proper balance among types of projects. 3. Fund the correct number of projects. 4. Ensure that projects are aligned to organizational strategies.	Portfolio management is accomplished by: 1. Ranking projects (using one of many ranking methods). 2. Assigning projects to strategic categories (determined by separate analyses and/or senior management). 3. Establishing funding levels for each strategic category. 4. Funding only those high priority projects in each category that fall within the funding limits.	Another portfolio approach is to examine each project in light of its ability to strengthen the project portfolio relative to other alternative projects. If it enhances the portfolio, then one or more other projects must be dropped to make room for the new project.
Strategic technology alliances	Strategic alliances are relationships—usually long-term—between organizations to jointly develop and apply important technologies, and that go beyond conventional technology supplier and user roles. Sometimes these alliances represent formal partnerships or joint ventures.	The purpose of a strategic technology alliance is to achieve common—or at least compatible—goals between two or more organizations, and to share control, costs, risk, and rewards from the partnership. Such alliances are typically used when research costs and risks are high or where unusual synergies can be gained by collaboration.	Process: 1. Identify and assess alliance opportunity. 2. Define objectives, approach, responsibilities for each partner, milestones, and end-state conditions and methods. 3. Establish decision-making process and conflict-resolution procedures. 4. Document all agreements 5. Implement and manage alliances, with frequent communication and interactions between partners.	Achieving effective strategic alliances is not easy because of the difficulties in sharing decision-making and control, and inherent differences in objectives, capabilities, and culture among the participants. Like human relationships, all participants must share a common purpose and have a willingness to compromise.

Tool	Description	Purpose	Approach	Comments
Cross-functional teams	Teams consist of representatives from the various functions involved in research and product development.	The purpose is to ensure that the functions participating in the team are adequately represented in terms of their viewpoints and concerns, thereby resulting in better focused research and faster and easier transition to product status.	Process: 1. Determine initial team composition and leader. 2. Establish or confirm team charter, objectives, ground rules, and interaction modes. 3. Form and operate team. 4. Report results and modify team as required.	The formation and management of cross-functional teams is more of an art than a science, and the overall effectiveness of the team depends on how it is structured; geographical location(s); methods of interaction; how it is empowered; managed and led; and the capabilities and personalities of the individual members. The size and composition of the team will change as the project grows and progresses through the stage-gate development phases.
Advisory and review committees	Use of a carefully selected panel of experts to ensure credibility, objectivity, and relevance of research programs, planning methods, and management techniques.	The use of advisory and review boards provides the following benefits: 1. Increases the quality of the program planning process. 2. Increases communication with other researchers within and outside the organization. 3. Reduces research overlap or duplication. 4. Provides a verification of the research priorities and minimizes gaps.		

Tool	Description	Purpose	Approach	Comments
SWOT (strengths, weaknesses, opportunities, and threats) analysis	SWOT analysis is a technique for examining how an organization can perform relative to its mission, capabilities, and environment.	The technique: 1. Provides an overall view of the organization and the factors that affect its performance. 2. Establishes a baseline for creating strategies that address key issues. 3. Points to critical issues that must be addressed if an organization is to succeed.	Typical steps in a SWOT analysis: 1. Dialogue among key decision-makers concerning SWOTs. 2. Prepare key background reports. 3. Develop list of consensus SWOTs. 4. Identify possible strategies in response to SWOTs.	1. SWOT analysis is normally a part of a conventional strategic planning process. 2. Requires a good understanding of mission. 3. It is usually better to examine external issues before looking at internal issues in order to keep proper perspective and balance.
Balanced scorecards	A planning and performance measurement technique and integrated framework that balances four performance dimensions: 1. Customer perceptions of how the organization is performing. 2. Internal perceptions of how the organization is doing and what it must excel at. 3. Innovation and learning performance. 4. Financial performance.	The balanced scorecard technique provides a more evenhanded view of an organization's operations and performance than traditional financial measurement methods. This method also helps ensure that quantifiable measures of effectiveness are tied to the organization's strategies, and serves as a means of communicating to employees and external stakeholders the outcomes and performance drivers that will lead to achieving its mission and strategic objectives.	Balanced scorecard approach steps: 1. Establish scorecard team. 2. Develop or confirm mission, values, vision, and strategies. 3. Select scorecard perspectives (e.g., customer, financial, employee learning, and internal processes). 4. Collect and analyze relevant information. 5. Create and test strategy maps. 6. Develop performance measures, targets, and initiatives. 7. Develop and initiate implementation plan.	Although originally developed for profit-making companies, balanced scorecards are becoming increasingly used by nonprofit organizations to measure performance and communicate strategies and values.

Tool	Description	Purpose	Approach	Comments
GOTChA (Goals, Objectives, Technical Challenges, Approaches)	GOTChA is a planning technique that maps systems-level performance and technology goals to R&D activities needed to achieve the goals.	GOTChA provides a framework for determining goal-directed S&T program requirements. It helps ensure that S&T funds are spent in a focused and productive manner and provides a tool for monitoring progress of individual technology efforts.	The GOTChA process involves the following steps: 1. Establish quantitative system-level technology goals. 2. Determine technology developments needed to meet the goals. 3. Develop a plan to carry out the R&D. 4 Validate road maps with larger stakeholder community.	
Conventional strategic planning	A structured long-range planning method that is widely used to produce fundamental decisions and actions that shape and guide what an organization is and does.	The method is used to: 1. Turn mission and vision statements into actions. 2. Bring structure and measurement to organizational planning. 3. Develop strategic priorities. 4. Communicate priorities and guide decision-making. 5. Assess future scenarios and select strategies to deal with outcomes.	Typical strategic planning steps include the following: 1. Determine or affirm mission and goals. 2. Study internal and external environment (situation analysis). 3. Identify strategic issues. 4. Formulate and assess strategies. 5. Develop plan. 6. Implement plan. 7. Assess progress.	1. Widely used since the 1970s, but has fallen out of favor with some because of failure to predict the future. Sometimes viewed as "rain dancing" with no effect on the weather. 2. To be successful, must have top management support and be integrated with other management functions. 3. Requires structure and resources. 4. Usually done on an annual basis. 5. Takes several years and cycles to implement effectively.

Tool	Description	Purpose	Approach	Comments
Technology road mapping	A multistep process that captures important trends, identifies future technology needs, and develops a strategic research plan to satisfy these needs.	Road maps capture the driving issues shaping future technology needs in order to enhance communication and insight. The process provides a structured forum for interaction among stakeholders for sharing knowledge and capabilities to ensure important long-term needs are addressed.	Process: 1. Collect and analyze background information on technology trends, applications, and unmet needs. 2. Assemble a balanced team of stakeholders (researchers, technology suppliers, users, etc.) 3. Facilitate the team to: a. Create a long-term vision of technologies and applications. b. Determine barriers that must be overcome to achieve the vision. c. Identify research needed to overcome the barriers. d. Establish priorities for the research efforts and organize into road maps. e. Determine resource requirements and how the research will be performed.	Although road mapping can be a useful planning tool, it must be used cautiously to avoid several common pitfalls, such as maps that do not allow for unplanned innovations or undue political influences and maps that emphasize perceptions rather than technical realities. Unfortunately, road mapping tends to yield consensus views of the future, thus minimizing the likelihood of pursuing nonconventional, breakthrough solutions.

Tool	Description	Purpose	Approach	Comments
Modeling and simulation	A model is a mathematical, physical, or procedural representation of a system, component, technology, entity, phenomenon, or process. A simulation is a method of implementing a model over time. A simulation brings the model to life and shows how a particular object or phenomenon will behave. There are several different types of simulations, including virtual simulations, constructive simulations, and live simulations.	Modeling and simulation is used to investigate, understand, or provide experimental stimulus to either (1) conceptual systems or technologies that do not exist or (2) real systems that cannot undergo experimentation due to resource, security, safety, or other limitations. The use of such tools can: 1. Reduce time and cost to develop new technologies and concepts. 2. Improve performance of technologies and advanced concepts. 3. Identify key variables that must be addressed during research. 4. Determine major risks and "show stoppers." 5. Quickly provide first-order estimates of performance and cost.	Modeling and simulation typically involves the following steps: 1. Investigate the technology or system to be modeled. 2. Construct an appropriate model that addresses the variables of interest to the research. 3. Verify and validate the model. 4. Exercise the model by means of simulations over suitable ranges of input and initial conditions. 5. Analyze the results and modify the model is necessary.	Modeling and simulation are becoming increasingly important tools in DoD research as part of new policies focusing on simulation-based acquisition.

Tool	Description	Purpose	Approach	Comments
Project scoring models	A variety of methods used to rank research projects based on assessment rules, weighted criteria, or value analysis.	To evaluate and rank alternative research projects in a rational manner to ensure consistency with research objectives and optimal use of resources.	The approach used depends on the modeling process selected. For weighted criteria techniques, the steps might include the following: 1. State the decision to be made. 2. Develop research objectives. 3. Classify objectives into MUSTs and WANTs. 4. Weight the WANTs. 5. Identify the alternatives (in this case, S&T projects or technology areas). 6. Screen the alternatives through the MUSTs. 7. Compare (score) the alternatives against the WANTs. 8. Identify adverse consequences. 9. Make the best balanced choice.	Any scoring model must be tailored to fit the context for which is being used. The approach selected will influence the level of effort required, the quality of the results, and the transparency of the process.

Tool	Description	Purpose	Approach	Comments
Cause-and-effect (fishbone) diagrams	This technique used to graphically find root causes of problems and relate solutions to problems.	Enables teams to focus on core issues and not symptoms or differing personal interests. Creates a graphic view and team consensus of problems and solutions.	Steps in creating a cause-and-effect diagram: 1. Identify effect to be analyzed. 2. Generate causes, in increasing detail, by brainstorming or checklists. 3. Construct the fishbone diagram.	
Visionics	A planning and assessment approach developed by the Army Night Vision Lab to quantify and model equipment performance.	This tool provides objective criteria for assessing system and component performance. It is used for R&D planning before investment by: 1. Establishing baseline performance criteria. 2. Enabling performance/cost trade-offs prior to project execution. 3. Justifying the pursuit of new research directions. 4. Uncovering modeling improvements that can lead to operational efficiencies. 5. Leading to improved decision-making at all levels.	The Visionics process uses the following steps: 1. Develop performance models based on empirical data. 2. Refine models based on operational testing. 3. Use models to assess R&D options.	The Visionics modeling concept has been applied to night vision technology. Whether this approach can be expanded to apply to systems as complex as those being developed by MDA would need to be investigated.

Tool	Description	Purpose	Approach	Comments
Technology readiness levels (TLRs)	A qualitative scale used to describe the maturity level of a technology. It is a system of descriptors originally developed by NASA to standardize the status of technology with respect to ultimate operational use.	Provides a basis for comparing different technologies, determining the risk associated with use of an emerging technology, and forecasting when a technology will reach maturity.	A TRL is a subjective score that rates technologies on a scale of one to nine, with a score of one being the highest risk and lowest readiness, and a score of nine being lowest risk and highest readiness. TRLs 1 to 6 are generally pursued independently of a particular system, although they may have specific system targets. TRLs 7 to 9 are associated with the transition of the technology to a specific system application.	TRLs have certain disadvantages: 1. Inherent subjectivity of scores. 2. The scores are based primarily on level of testing, which may not reflect the true level of risk. 3. They do not reflect other non-technical risk factors.
Decision trees	A technique for displaying and analyzing decisions and values of chance outcomes as branches coming out of nodes in a tree structure.	Enables users to break broad goals and problems down into increasing levels of detail and alternative actions. Decision trees facilitate analysis of alternative outcomes and encourage expanded thinking about issues and possible solutions.	Decision trees use the following steps: 1. Define the goal or problem statement. 2. Generate major tree headings (e.g., goal, means, and methods). 3. Break the goal or problem statement into increasing levels of detail using the headings as a guide. 4. Assign probabilities and resources to appropriate branches. 5. Determine overall probabilities and resources for each outcome.	A number of variations exist for how to define branches and assess impact.

Tool	Description	Purpose	Approach	Comments
Affinity diagrams	This tool is used by teams to generate a large number of options and issues and summarize them into natural groupings.	Encourages participation by all team members and breaks down communication barriers. Allows nontraditional connections between ideas and enables breakthroughs to emerge naturally. Overcomes team paralysis and fosters ownership of results.	The use of affinity diagrams typically follows these steps: 1. Frame the problem by discussing its scope and needs to be solved. 2. Brainstorm ideas or issues affecting the problem or solution. 3. Sort ideas into related groups. 4. Use group consensus techniques to create group headings and subheadings.	
Interrelationship digraphs (IDs)	A technique used to systematically identify, analyze, and classify cause-and-effect relationships.	Explores the cause-and-effect relationships among all issues, including the most controversial. Encourages team members to think non-linearly. Allows key issues to emerge naturally and systematically surfaces assumptions and reasons for disagreement. Helps identify root causes even when data do not exist.	Procedure: 1. Agree on problem statement. 2. Assemble knowledgeable team. 3. Identify and display all issues. 4. Use matrixes to determine influence relationships between issues. 5. Construct final ID. The relationship matrixes can also be used to analyze issues and display results.	

Tool	Description	Purpose	Approach	Comments
Prioritization matrixes	A method for systematically weighing options to determine priorities.	Forces a team to focus on the best solutions, thereby increasing likelihood of success. Quickly surfaces basic disagreements so they can be resolved early in the process. Minimizes chance of pursuing "pet rocks" or hidden agendas.	1. Team agreement on ultimate goal to be achieved. 2. Create list of criteria. 3. Using matrix, weight criteria against each other to determine relative weight for each. 4. Using other matrixes (for each criteria), weight the options against each other to determine relative weight of each. 5. Use a summary matrix to compare each option to all criteria, thereby determining overall priorities.	Typically used with small teams (less than 10 people), few options (10 or fewer), and few criteria (6 or fewer). Several variations on this approach exist for larger problems or when the problem involves cause-and-effect relationships. Similar to the "Analytic Hierarchy Process" for decision-making.
Influence diagrams	A technique for visual representation of a decision problem.	Provides an intuitive means of identifying and displaying essential elements, including decisions, uncertainties, and objects, and how they influence each other. It provides a high-level qualitative model that can be used as a basis for constructing a more detailed quantitative model. Helps to develop a shared understanding of key issues. Helps to conceptualize the model before adding mathematical detail, and simplifies communication to others.	Process: 1. Construct diagram from nodes, whose shape represents various types of attributes (e.g., decisions, chance variables, etc.). 2. Connect the nodes using directed arrows to represent influences. These diagrams are often generated by computer programs that allow insertion of functions within nodes and creation of complex, hierarchical model structures.	Similar to decision trees but show the relationships between variables more clearly and efficiently. Related software includes: Analytica, Lumina Software (www.lumina.com).

Tool	Description	Purpose	Approach	Comments
Morphological matrixes (Quality Function Deployment)	A systematic planning and problem-solving tools for translating customer requirements into engineering requirements of a product. Sometimes referred to as the "house of quality" technique.	Creates high-level customer buy-in and group knowledge of the product and strengthens interfunctional teamwork.	Basic steps: 1. Brainstorming to define customer needs and engineering characteristics (product or process attributes) for satisfying these needs. 2. Create interrelationship digraph that shows cause-and-effect relationships among critical issues to determine key drivers and outcomes. 3. Create a “house of quality” diagram that illuminates the most important engineering characteristics in terms of their influence on customer requirements. 4. Use the above information to define a baseline solution.	Some individuals define morphological matrixes in a more simplistic manner, mainly as an array of engineering characteristics versus technology options. This allows the designer or decision-maker to visualize all possible alternatives for a given engineering characteristic. Although useful, this alternative definition is not as analytically powerful as the Quality Function Deployment approach.

Tool	Description	Purpose	Approach	Comments
Structured brainstorming	A structured process for: (1) establishing an innovation team, (2) investigating needs or problems, (3) creating breakthrough ideas, (4) evaluating best solutions, and (5) developing action plans.	Used to: (1) quickly develop radical solutions, (2) improve teamwork and commitment to action, (3) reduce fear of competition or project obstacles, (4) create a high volume and wide variety of actionable ideas, and (5) increase appreciation for thinking outside of the box.	Many companies offer structured brainstorming services: Thinkubator and IlluminAction (www.solutionpeople.com) Several variations to process exist, including unstructured approaches.	Other commercial brainstorming tools include the following: 1. KnowBrainer (www.solutionpeople.com) 2. Creator Studio (www.compxpressinc.com) 3. ThoughtPath (www.thoughtpath.com) Sometimes “reverse brainstorming” is used to rip apart current solutions and use these identified problems as a starting point for creative brainstorming.
Nominal group methods	A group of methods for building team consensus about priorities by combining individual team member rankings.	Used to ensure equal team member participation in ranking of issues and solutions. Focuses on consensus results. Builds team commitment to outcome.	Process: 1. Generate lists of issues, solutions or recommendations. 2. Discuss and clarify lists, eliminating duplicates. 3. Each team member rank or vote on alternatives. 4. Combine team scores to establish overall ranking and priorities.	Many alternative team scoring methods exist.

Tool	Description	Purpose	Approach	Comments
Internet surveys	The use of Web-based surveys of appropriate experts and communities.	Provides a relatively low-cost and rapid way of automating the survey process. In addition to speed and low cost, such surveys also enable rapid data analysis and an ability to easily modify the survey instrument.	Process: 1. Develop survey instrument/questionnaire 2. Establish survey Web site. 3. Notify participants or solicit survey respondents. 4. Conduct survey. 5. Analyze results.	Commercial Internet-based services are available but are used mainly for consumer-related on nonsensitive surveys. This technique works best for surveying a well-defined and accessible community of experts.
Expert opinion	A straightforward survey of experts concerning the importance or likelihood of technologies or events.	This technique is typically used when other survey or forecasting techniques are not available. The purpose is to ensure that the best expertise possible to examining the factors and issues in question. This is particularly true for complex issues that involve nontechnical factors, such as economic, political, or social trends.	Process: 1. Identify the most suitable experts. 2. Select an appropriate survey mechanism (phone, mail, email, face-to-face, workshop, etc.) 3. Conduct survey. 4. Analyze results.	Success depends on balance and expertise of individuals included in survey and mechanism selected for data collection. Workshops are problematic due to political issues and the dynamics of human interactions.

Tool	Description	Purpose	Approach	Comments
Delphi forecasts	A forecasting technique that uses judgmental techniques by surveying appropriate experts in a series of rounds with feedback between rounds.	Used to estimate the impact of a technology and the confidence and timing of achieving that impact. Especially useful when data are lacking, such as during new product development.	Surveying of experts is usually done using questionnaires, which may be administered by means of face-to-face interviews, mailed surveys, or Web-based interactions. The results are of survey rounds are fed back to the experts between rounds so they can benefit from the analyses of the group responses.	Projections developed by Delphi panels are believed to be more accurate than forecasts based on unaided judgment. However, there is limited direct evidence of the accuracy of forecasts using the Delphi method.
S-curve forecasting	This technique based the forecast of a technical parameter based in a three-phase model of progress: (1) incubation, (2) rapid growth, and (3) maturity, which collectively yield an S-shaped growth curve of technical capability versus time.	This method yields forecasts that are historically valid from a technical market development viewpoint. The technique is also useful for predicting when the technical performance of a new technology will reach a particular level or for estimating how much investment is needed to achieve a certain capability. In some cases, multiple S-curves are cascaded to forecast the growth and substitution of families of technologies.	The approach used depends largely on how early in the S-curve the estimate is made. Early on, when little data are available, initial estimates based on expert opinion are used to develop the S-curve; later, when some progress has been made and data are available, estimates are based on standard formulas and curve-fitting techniques. The natural or physical upper limit to the capability is also estimated to establish a ceiling on capabilities which the S-curve approaches asymptotically.	This technique only applies to those situations when the technology is market driven, the attributes desired by the market are known, and technical progress is the direct result of financial investment.

Tool	Description	Purpose	Approach	Comments
Fischer-Pry analysis	A method for forecasting the substitution between technologies or products based on S-curves, where the new technology follows the classical S-curve for growth, and the declining technology follows a reverse S-curve.	Provides one of the most accurate forecasting methods for technology substitution based on actual market data, especially in early and mid stages of growth.	Process: 1. Collect data on existing and substituting technologies and calculate the market fractions represented by both. 2. Plot market fractions on log-linear graph paper and fit appropriate line to data. 3. Plot substitution curve and forecast future technology growths and declines over time. 4. Conduct sensitivity analysis to validate assumptions and determine robustness of the forecasts.	Only addresses technology substitution, not market size. Also, the technique becomes less accurate as the market dynamics become more complex and involve nontechnical issues.
Precursor trend analysis	Technique bases forecasts on an analysis of precursor developments, particularly growth in relevant patents and technical publications.	Method is used to forecast which new technologies might emerge in the future and to determine when they will start moving up a traditional S-curve and at what rate they will advance. It is particularly useful when estimates are needed before the existence of concrete market data.	1. Identify analogous precursor phenomena and determine appropriate correlations between precursors and market entry time lags. 2. Track precursors for technologies of interest. 3. Forecast future technical market entry and capability growth based on correlated relationship data. 4. Analyze any potential reasons why model may not be valid.	Method requires some familiarity with how similar technologies behaved in the past to estimate time lags between patents and technical publications and actual market entry. It relies on the viewpoint that patents represent "seeds" of research investments that will grow in the future and that technical papers represent progress leading up to practical implementation of the technology.

Tool	Description	Purpose	Approach	Comments
Relevance trees	A normative technique for breaking down the forecast for a complex technology or system into a hierarchy (or tree) of levels of more limited forecasts for supporting technologies or alternative solutions. These lower-level forecasts are evaluated to determine their relevancy, which is then used to compute an overall forecast.	Relevance trees are used to: 1. Establish the feasibility of a specified normative goal or objective. 2. Identify alternative methods for satisfying the technical requirements at each level of the tree. 3. Determine the required performance levels for each of the major elements of the systems or subsystems, including those critical for success. 4. Focus on areas where significant breakthroughs are needed to achieve overall system requirements. 5. Determine the optimum components of an R&D program to support the development.	Procedure: 1. Establish overall objectives for the technology or system. 2. Determine hierarchical tree levels. (One approach is to use the following levels: overall objective, major subsystems, alternative approaches, R&D projects.) 3. Construct the tree—several iterations may be needed. 4. Estimate timing, cost, and relevancy for each R&D project. 5. Evaluate relevancy and timing of projects to develop overall forecasts and content of optimal R&D program. 6. Validate forecasts with stakeholders.	Sometimes referred to as an “objective tree.” This technique exemplifies the overlap between the tool categories used in this report. Although relevance trees can be used for forecasting, they can also be used for planning and analysis. For example, the GOTChA technique, discussed as a planning and road-mapping tool, is essentially based on relevance trees.

Tool	Description	Purpose	Approach	Comments
Scenario analysis	Forecasts are developed based on alternative scenarios that can shape the future.	Scenario analysis provides forecasts that explicitly recognize that future events are not deterministic by examining the impact of several feasible alternatives. Also helps decision-makers become more sensitive to signals of impending change.	Process: 1. Construct alternative scenarios, including best and worst cases. 2. Estimate the likelihood of each scenario occurring. 3. Assess the impact of these scenarios on S&T planning. 4. Identify and track “markers” that can be used to determine the likelihood of each scenario occurring.	
Cross-impact analysis	A forecasting method that takes into consideration the possible interactions between multiple future events. In its simplest form, it is a matrix of interactions between specific of occurrences or developments.	The purpose of cross-impact analysis is to clarify the interactions between possible future events. In more complex forms, it involves calculations of interlinked probabilities of events through which possible future pathways can be traced.	Process: 1. Compile a comprehensive list of possible future events or developments. 2. Create a cross-impact matrix that indicates the relative impact of one event on the likelihood of another occurring. 3. Compute the overall likelihood of an event based on the occurrence of the other events in the list.	This technique is particularly useful for forecasting the impact of S&T policies. It can also be used to evaluate the impact of non-occurrences.

Tool	Description	Purpose	Approach	Comments
Backcasting	Backcasting is a method of reverse forecasting future events, starting with the desired future goal. It is sometimes referred to as "Apollo forecasting" because it was used in the Apollo program to forecast how a human would be placed in the moon.	The purpose of backcasting is to identify a cause-and-effect chain that can lead to accomplishment of grand challenges. It can also be used to evaluate the degree to which a desired goal can be achieved.	Process: 1. Determine future objective or grand challenge. 2. Specify particular goals, constraints, and targets. 3. Describe the current situation. 4. Identify the important factors that will influence the future. 5. Develop alternative scenarios that could lead to achieving the future objective. 6. Undertake an impact analysis to compare the anticipated results of the scenarios with the desired future state.	This technique is very similar to relevance trees and technology road mapping but possibly more complex.

Tool	Description	Purpose	Approach	Comments
Management groupware	Integrated, Web-based collaborative tools for project planning, management, and execution.	Groupware provides a mechanism for collaboration among staff and research performers in order to increase interaction, communications, speed, and effectiveness by tracking deliverables, tasks, issues, and budgets.	Although several commercial groupware systems are available to perform this function, most installations need to be tailored to the unique processes and needs of the using organization.	Examples of groupware include: LiveLink for Program Management from Open Text (www.opentext.com).
Mind maps	A computer-based method for brainstorming, planning, meeting facilitation, and implementation of action plans.	Used to: 1. Electronically capture information. 2. Understand concepts faster. 3. Communicate more clearly. 4. Improve team collaboration. 5. Increases productivity promotes team interactivity and individual contributions. Enables immediate distribution of results.	Mind maps automate the following functions: 1. Capturing ideas. 2. Transcribing ideas into electronic format. 3. Organizing data and relationships. 4. Creating action plans. 5. Distributing information electronically.	Trial software, reference, and examples: www.mindjet.com. Similar software products include: 1. Dynamic Thinking, VisiMap. 2. Inspiration Software, Inspiration. 3. Norcan Data AS, Visual Mind. 4. SimTech USA, MindMapper.
Ethnographic research	An “anthropological” style of research to uncover unmet user (customer) needs.	The primary purpose is discovery of unmet user needs. However, the technique is also useful for developing a better understanding of user requirements and priorities in general.	Ethonographic research involves spending time with users to observe their activities, problems, frustrations, and unmet needs in order to uncover new solution possibilities that even the user does not recognize.	Sometimes called "fly-on-the-wall" research.

Tool	Description	Purpose	Approach	Comments
Lead-user interaction	Identification of unmet user needs by interaction with lead (or innovative) users.	Used to generate innovative solution concepts by working with leading users with unusual insight and high expectations. Such lead users also serve as valuable sounding boards or test beds for new concepts from other sources. They also are important individuals to have as workshop participants.	Process: 1. Identify target user community and lead users. 2. Interact with lead users though visits and workshop participation. 3. Establish collaborative relationship with key individuals.	
Technology monitoring	Centralized abstracting and monitoring system which circulates information throughout an organization from scientific and technical literature, patents, journals, technical reports, conference proceedings, etc.	Monitoring is performed to: 1. Detect developments that are likely to affect future product designs. 2. Alert technologists as to what they should be looking for. 3. Assess the significance of new developments. 4. Serve as a corporate memory concerning important technical developments.	Such systems need to be custom designed to meet the needs of the organization. They generally include both formal and informal flows of information to be effective.	
Staffing guidelines	Various techniques for staffing research-management positions with individuals that are most suitable from the standpoint of creativity, entrepreneurship, and similar traits.	Increase effectiveness of research staff based on screening of personality traits and proper incentives to encourage creativity and risk taking.	This is a relatively new field that does not have a well-established approach. Some organizations have developed special personality tests. Use of IPAs could be another approach that could be used here	Because of personnel restrictions, implementing this method would probably require special approval from personnel leaders (e.g., Office of Personnel Management).

APPENDIX D

MISSILE-RELATED SIMULATION MODELS[1]

Model Name	Description	Point of Contact
Battle Area Regions Threatened (BART)	BART is a PC-based model used to conduct analyses of ballistic missile defense architectures. It models radars, threat missiles, interceptor missiles, and space-based warning. It outputs data on, among other things, engagement opportunities, kill assessment opportunities, and intercept angles. BART allows an analyst to design an arbitrary defensive architecture composed of ground-based radar sensors and ground-based ballistic interceptor missiles. The performance parameters of the radars and interceptor missiles as well as their locations are all user defined. BART has the capability to simulate the early warning afforded by space-based launch detection sensors such as the Defense Support Program (DSP) or Space Based Infra Red System satellites.	NORAD Ms. Isabelle Julien 719-554-3781 isabelle.julien@peterson.af.mil
Commander's Analysis and Planning Simulation (CAPS)	CAPS is used to solve problems involving Theater Air and Missile Defense and Ballistic Missile Defense. It covers the most common missile types, threats and friendly defenses as well as the Airborne Laser, Ground Based Interceptors and the Aegis LEAP Interceptor. It is PC based.	SPARTA Inc., Mr. Dave Eissler CAPS Program Office 703-797-3068 caps.questions@sparta.com.
Extended Air Defense System (EADSIM)	EADSIM is a system-level simulation used by combat developers, materiel developers and operational commanders to assess the effectiveness of theater missile defense and air-defense systems against the full spectrum of extended air-defense threats. EADSIM models fixed- and rotary-wing aircraft, tactical ballistic missiles, cruise missiles, infrared and radar sensors, satellites, command-and-control structures, sensor and communications jammers, communications networks and devices, and fire support in a dynamic environment that includes the effects of terrain and attrition on the outcome of the battle. The tool provides analysts and training audiences insights into theater missile defense architecture, battle management, system employment for maximum effectiveness, force structure analysis, and mission planning.	Army Space and Missile Defense Command Mr. Jim Watkins, jim.watkins@smdc.army.mil 256-955-1681 or Mr. Page Stanley Teledyne-Brown Engineering (TBE) page.stanley@tbe.com 256-726-1866 or www.eadsim.com

1 "Space, Missile Defense & Information Operations Models and Simulations Catalog (for USSTRATCOM)," 26 August 2002, (http://www.msiac.dmso.mil/spug_documents/spacecatalog26aug.doc).

Model Name	Description	Point of Contact
GPS Interference and Navigation Tool (GIANT)	GIANT is a constructive and repeatable engagement/mission-level simulation that calculates the impact of navigation performance on warfighter measures of effectiveness (e.g., target kills). A GIANT scenario consists of a GPS/INS-equipped platform moving over digital terrain (i.e., digital terrain elevation data), on a WGS-84 Earth, under a moving GPS constellation transmitting multiple codes on multiple frequencies. GIANT can represent any air or ground vehicle with or without weapons. Weapons also have GPS/INS navigation systems and the launch platform to weapon handoff event is modeled. As an option, any number of stationary or moving GPS jammers can be present. Target miss distance and probability of kill is thus traceable to the weapon and the launcher.	SMC/CZE 1LT Amon Dothard amon.dothard@losangeles.af.mil 310-363-3124 or Mr. Steve Friedman Veridian Engineering www.veridian.com 937-476-2509
Joint Warfare System (JWARS)	JWARS is under development to be a state-of-the-art, constructive simulation that provides a multisided and balanced representation of joint theater warfare that is capable of use in analysis of planning and execution, force assessment, system effectiveness and trade-off analysis, and concept and doctrine development and assessment. It will be a balanced warfare representation including C4, ISR and logistics and will focus on the operational level of war. It will replace MIDAS and TACWAR.	Mr. Don Bates JWARS Joint Program Office 703-696-9490 or JWARS Help Desk 913-684-8080 or https://www.jointmodels.smil.mil
Missile Defense Space Tool (MDST), formerly Portable Space Model (PSM)	MDST provides the capability to support live or simulated exercises by injecting missile warning message sets into operational communications and simulation networks. MDST contains real-time models designed to provide a representation of the Defense Support Program, the Satellite Based Infrared System, and elements of the Theater Event System at a sufficient level of fidelity to support exercises while operating in real time. It notifies theater commanders of theater ballistic missile launches via the Tactical Information Broadcast System and the Tactical Related Applications Data Dissemination System.	JNIC MAJ Dave Silvernail 719-567-9373/0766
Lightning	Lightning is a strike-campaign-level simulation used to support analyses of the operational contribution of space systems (e.g., ISR, navigation, weather, communications) using operational metrics such as targets destroyed over time, time to achieve operational phase goals, time to halt, and attrition over time. Lightning is an aggregated model that supports quick turnaround studies with very rapid execution, rapid modification, and rapid database development.	Northrup-Grumman/IT-TASC Lightning Solutions Dr. Gregg Burgess gburgess@northrupgrumman.com 703-793-3700 x2310

Model Name	Description	Point of Contact
National Air & Space Model (NASM)	NASM is the Air Force component of the Joint Simulation System (JSIMS). It is the successor to the Air Warfare Simulation (AWSIM). NASM is developing the mission space objects (systems, organizations and procedures) JSIMS will use to provide the functional capability to represent the full range of aerospace power applications in a joint synthetic battlespace for both Air Force specific and joint training. Applications include training and readiness, education, doctrine development, situation assessment, and the formulation, assessment, and rehearsal of operational plans. The IOC version of NASM will likely include a limited depiction of all satellites (basic orbital characteristics) and higher fidelity models of missile warning (Defense Support Program & Space Based Infra Red System), navigation (GPS), some satellite communications, and foreign space control.	LtCol Emily Andrew AFMC ESC/CXC 781-377-6421 emily.andrew@hanscom.af.mil or Mr. Paul Driscoll 781-377-2670 Paul.driscoll@hanscom.af.mil
Satellite & Missile Analysis Tool (SMAT)	SMAT is a comprehensive two-dimensional and three-dimensional animated visual modeling tool for analysis of orbiting bodies, ballistic missile trajectories, and their relationship to Earth. SMAT provides a fully modeled Earth with detailed geographic and political boundaries, has the capability to zoom and rotate the viewing position of Earth, and provides accurate Sun position and illumination. Databases within SMAT contain the parameters for the Tactical Warning/Attack Assessment System, the Air Force Satellite Control Network, and the Space Surveillance Network sensors. SMAT allows complete control of all displayed sensor parameters, both ground and space-based, and allows importing, editing and saving of additional sensor parameters. SMAT provides the capability to model ballistic missile launch profiles, both strategic and theater, from any point on the surface of Earth.	Ms. Kathy Gue USAF/SWC/DOG (Space Warfare Center) kathleen.gue@swc.schriever.af.mil 719-567-9289

Model Name	Description	Point of Contact
Satellite Tool Kit (STK)	STK 4.0 (basic) is a free commercial off-the-shelf product that provides sophisticated modeling functions for space- and ground-based objects, such as satellites, ships, aircraft, and land vehicles. Functions included in the free version of the software include vehicle propagation, determining visibility areas and times, and computing sensor pointing angles. Free STK provides animation capabilities and a two-dimensional map background for visualizing the paths of vehicles over time. Results can be generated in both textual and graphical formats. Additional modules can be purchased to provide enhanced computational and visualization capabilities. In particular, STK's Visualization Option provides dynamic three-dimensional display of STK scenarios. A host of additional modules are available to provide detailed analyses for such tasks as determining satellite coverage over time, visibility-related access for networks of objects, rapid analysis of close encounters between orbiting objects, realistic missile flight modeling, are detailed modeling of radar systems and satellite communications link analysis. It addresses mission planning, launch, and ballistic missile flight. STK is used to examine alternative deployments of satellites within constellations and analyze alternative coverage of combinations of satellites.	Analytical Graphics, Inc. Mrs. Tina Cox 719-573-2600 or 1-800-220-4STK tcox@stk.com or www.stk.com
Strategic and Theater Attack Modeling Process (STAMP)	STAMP is a ballistic-missile and space-launch-vehicle flight generator and engineering analysis tool. It can model missile flights from launch to impact and present extensive flight characteristics and trajectory descriptions using a wide array of graphical and tabular outputs. STAMP can also model numerous U.S. and foreign space launch vehicles from launch to orbital insertion. STAMP features an easy-to-use operator interface using windows and click-type menu selections. STAMP is driven by detailed engineering databases, developed and approved by the appropriate intelligence agencies, that have the parameters and values needed to model strategic and theater missiles as well as foreign space launch vehicles consistent with intelligence estimates. Portions of STAMP have been integrated into the SMAT to generate and process foreign missile trajectories for SMAT users. STAMP was developed by SAIC under the sponsorship of the Air Force National Air Intelligence Center.	1LT Tempalski 937-257-2356 rnt181@wpafb.af.mil or George Panson 937-257-2356 gmp268@wpafb.af.mil
Command and Control Warfare (C2W) Analysis and Targeting Tool (CATT)	CATT provides a simulation capability of an adversary's integrated air defense system and the capability for analysts to do sensitivity analysis on alternative actions. It includes end-to-end modeling of integrated air defense system processes such as detection, tracking, weapons allocation, communication, decision-making and engagement. The model's primary C2W actions include inserting and removing various user-defined flight paths and removing various communications links and radar posts.	AFIWC/SAA LtCol Ross Ziegenhorn raziege@afiwc.osis.gov 210-977-2427

Model Name	Description	Point of Contact
C4ISR, Space and Missile Operations Simulation (COSMOS)	COSMOS has been developed to support analysis of the performance of C4ISR, space, and missile systems. COSMOS explicitly models collection systems for SIGINT, IMINT, and HUMINT as well as surveillance systems using visible, IR, LADAR and RADAR technologies. The resources and associated time lines required to process, exploit, and disseminate the collected information are modeled using a flexible rule-based approach. COSMOS can also model systems in all Space Command mission areas including futuristic U.S. and foreign space control systems such as space-based lasers, ground-based lasers and kinetic energy antisattelite. The model is currently in use supporting OSD, Joint Staff, Air Force, Army, Navy, Marine, Office of the Space Architect, and classified customer analyses. COSMOS has been interfaced with community-accepted classified models to support analysis of current and future system architecture performance. COSMOS was developed and continues to be enhanced by the SAIC Pentagon On Site Team.	Jeff Knox SAIC 703-276-2116 JEFFREY.S.KNOX@saic.com.)
EDGE Developer Option	EDGE Developer Option is a commercial off-the-shelf set of visualization, simulation, and analysis tools and applications that allow users to create a rich synthetic environment and view the world from outer space to sea level. The foundation is the EDO Visualization Component. Additional components provide libraries for integrating imagery, maps, terrain, time, and weather. The Ascent tool for launch vehicle trajectory simulation component can also run as a stand-alone program.	http://www.autometric.com
Extended Air Defense Testbed (EADTB)	EADTB allows the analyst to model a broad range of military missile defense applications from the fire unit level to the theater level in a constructive simulation framework. Its object-based simulation architecture supports this range by allowing the user to develop system models called specific system representations. The user/analyst can place numbers of these tailored simulated systems on a host gameboard without having to rewrite other existing system models or modify the supporting architecture. A major strength of EADTB is the capability to model the BMC4I to the level necessary to answer complicated joint service interoperability issues. EADTB has obtained Defense Information Service compatibility and is pursuing High Level Architecture compliance at this time.	Army Space and Missile Defense Command (SMDC) Battle Lab Mr. Robert Karl 256-955-1685 robert.karl@smdc.army.mil
Global Positioning System End-to-End Model (GLEEM)	GLEEM was developed to assist in analysis of capabilities and vulnerabilities of Global Positioning Systems (GPS) and Inertial Navigation Systems (INS) in aircraft and guided munitions. GLEEM allows projection of GPS receiver performance in signal-lock maintenance while in a hostile or benign environment and simulates various combinations of antennas and receivers, on multiple platforms, with multiple jammers. Friendly interference platforms can be included as well.	AFIWC/SAV Lt Michael Perry mjperry@afiwc.osis.gov 210-977-2706

Model Name	Description	Point of Contact
Guardian	Guardian provides visualization and analysis of space system and architecture susceptibility to counter space threats. Guardian supports modeling of radio-frequency jamming, air-, ground-, and space-based laser phenomenologies, high-power microwave threats, and direct-ascent antisatellite systems. Guardian has the capability to model the interruption of system commanding, target imaging, and data download to ground stations. Guardian has been used to explore the effects of jamming the uplink communications of commercial satellite architectures.	Aerospace Corp. Dr. James Gee 310-336-5871
Integrated Modeling and Analysis Suite (IMAS)	IMAS models missile launches to determine origin and threat. It is used to develop inputs for Integrated Theater Warning and Attack Assessment end-to-end system integrity tests.	NORAD/USSPACECOM/J6C Mr. Ron Stephens ronald.stephens@peterson.af.mil 719-554-9704
Joint Integrated Contingency Model (JICM)	JICM is a global system developed to support balance assessment, contingency analysis, and military war gaming, and it addresses both major and smaller regional contingencies. The JICM is fundamentally a model of the world in which functional models of combat and visualization tools are embedded. The JICM includes models of force and logistics deployment, ground and air combat, and ballistic missiles and missile defenses. It provides the user with a graphical view of the developing combat situation. Over the course of a JICM run, histories of outputs are retained that can be plotted to highlight trends over time of analyst-selected measures of outcome. JICM modeling includes fire suppression by artillery, the effects of air interdiction on ground-force operations, combined arms effects, and tactical C3I effects. The effects of a wide variety of current and projected weapons are reflected in the JICM design, including advanced antiarmor systems (such as sensor-fused weapons).	Center for Army Analysis (CAA) CPT Max Moore 703-806-5593 moore@caa.army.smil.mil
Laser Threat Analysis System (LTAS)	LTAS is a comprehensive computer modeling and simulation environment for assessing the operational impact of optical directed-energy weapons and countermeasures. LTAS encompasses the solution spectrum from physical process models through comprehensive threat engagement models.	AFIWC/SAA Jack Labo jalabo@afiwc.osis.gov 210-977-2427
Model for Analysis of Sensor Coverage (MASC)	A Windows-based application for computing the terrain-masked line-of-sight coverage of ground, air and space-based sensors. Ground-based and airborne sensor coverage can be displayed in 2 and 3D while satellite line-of-sight coverage is displayed as a 2D map.	NORAD Ms. Isabelle Julien isabelle.julien@peterson.af.mil 719-554-3781

Model Name	Description	Point of Contact
NORAD / USSPACECOM Communications Simulation System (NUCSS)	NUCSS replicates the communications string of the missile warning component of Integrated Tactical Warning and Attack Assessment (ITW/AA). The model is maintained to reflect the current operational ITW/AA configuration. It provides (1) a performance audit of the current ITW/AA system under different threat scenarios and stress events such as link/node outages and degradation of the communications links, (2) a method to evaluate technical development of the system and to improve its performance, and (3) a road map for incorporating future mission capabilities into the ITW/AA communications system. The simulation is able to federate under High Level Architecture with other models.	NORAD Dr. Roy Mitchell roy.mitchell@peterson.af.mil 719-554-3718
Space Battle Manager Core System (SBMCS)	SBMCS furnishes warfighters with operationally relevant space planning and execution information and tools to support their missions. SBMCS is both a client/server-based information system accessible via Secure Internet Protocol Router Network (SIPRNET) and a deployable, non-server-connected, stand-alone system. The client/server-based configuration of SBMCS offers a comprehensive capability to assess the space order of battle, space system resource status, satellite overfly and look-angle information, and navigational accuracy to anyone on the SIPRNET.	AFSPC/DOO Capt David Stone 719-554-6207 or USSPACECOM/J36 David Newton david.newton@peterson.af.mil 719-554-3014 http://fwwebops.sbmcs.usspace.spacecom.smil.mil/index.html
Spacecraft Simulation Toolkit (SST)	The SST is an advanced, flexible development environment for the modeling of spacecraft and their environment. The SST is based on state-of-the-art simulation methods and accurate physical phenomenology. It's an object-oriented system consisting of software objects that simulate the various systems and subsystems of the physical spacecraft. The toolkit provides the ability to integrate the software objects together into a simulation of either a complete spacecraft system or a spacecraft subsystem. A key feature of the SST is its flexibility to be reconfigured to meet a wide variety of requirements in engineering, simulation, operations and training. Simulations that have been or are being developed include Ultra Lightweight Imaging Technology Experiment, Space-Based Radar AMTI/GMTI, Global Positioning System, Hyperspectral Imaging, Advanced Geosynchronous Studies, and the Next Generation Space Telescope.	Air Force Research Laboratory Dr. Rich de Jonckheere rich.dejonckheere@vs.afrl.af.mil 505-846-5054
Strategic and Theater Operations Research Model (STORM)	STORM will support in-depth analysis of the campaign-level contributions of air and space power. STORM is a multisided, object-oriented, stochastic computer simulation of military operations across the air, space, land, and maritime domains. The simulation is being designed and built expressly to examine issues involving the utility and effectiveness of air and space power in a theater-level, joint warfighting context.	USAF/AFSAA/SAAP Maj Bryn Turner 703-588-8674 bryn.turner@petnagon.af.mil

Model Name	Description	Point of Contact
System Effectiveness Analysis Simulation (SEAS)	SEAS is a PC-hosted, many-on-many, stochastic, theater-wide, multi-mission-level model. It is typically used for military utility analyses of present and future space systems to explore combat outcome sensitivities to C4ISR (command, control, communication, computers, intelligence, surveillance, and reconnaissance) operational concepts and force structures. By modeling the explicit causal link from sensor-to-shooter, SEAS is able to show the emergent nonlinear behavioral impact of C4ISR on spatial/temporal maneuver and attrition of terrestrial forces. SEAS 2 is a mission model in the Air Force analysis toolkit at http://www.xo.hq.af.mil/xoc/xoca/afsat	Capt Jeremy Noel (USAF/SMC/XRDM) 310-363-0765 jeremy.noel@losangeles.af.mil
Sensor Platform Allocation Tool (SPAAT)	SPAAT is an ISR force structure analysis tool. It is a mixed-integer program to select sensor architectures based on target coverage and cost constraints. SPAAT is used to determine the optimal mix of sensors and platforms required to accomplish the reconnaissance and surveillance mission. This optimization fits in the overall picture of the OODA (observe, orient, decide and act) loop at the orient/decide phase. ISR optimization bounds the feasible region of the trade space. An ISR mix that produces improved battlespace knowledge can be fed into campaign or mission models to illustrate/quantify the military worth of ISR.	AFSAA/SAF LtCol Jeff Smith 703-588-8682 jeff.smith@pentagon.af.mil
Warning	Warning is a PC-based, graphical strategic ballistic missile warning analysis model designed to estimate warning time available to specified targets from launches made from specified geographic areas. Its outputs can be interpreted as the probability that missiles fired from a particular area were detected and reported.	NORAD Ms. Isabelle Julien isabelle.julien@peterson.af.mil 719-554-3781

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14. ABSTRACT

This paper outlines how MDA could adapt and implement management methods developed in IDA Paper P-3764 (May 2003)—*Science and Technology in Development Environments*, to implement a strategically-focused S&T program. It presents an implementation blueprint that focuses on (1) radical innovation promotion; (2) strategic technology steering; (3) S&T networking and outreach; (4) analytical techniques for S&T planning and management; and (5) modeling and simulation.

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